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BLAST CAPACITY EVALUATION OF SINGLE REVETTED BARRICADES.(U)

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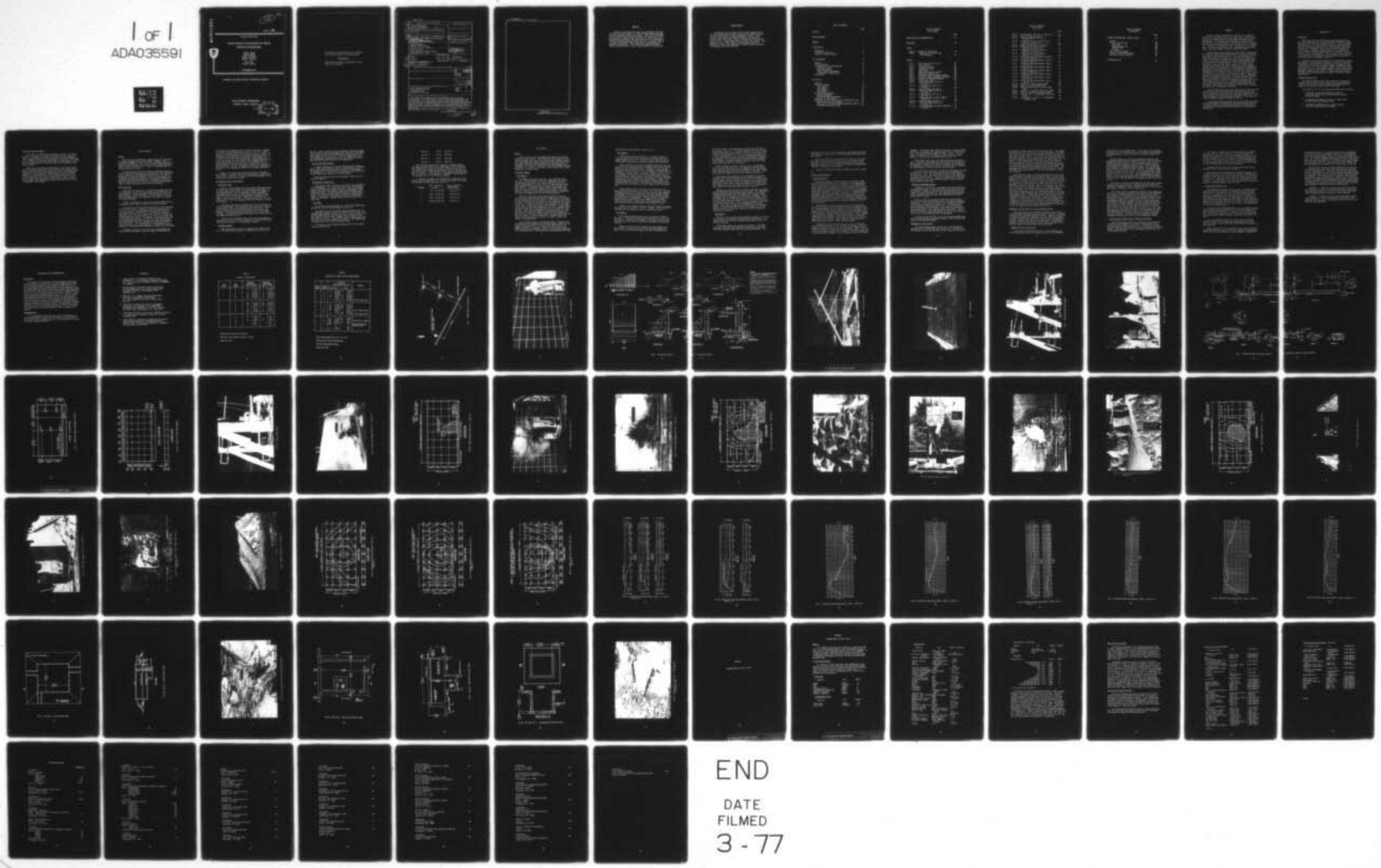

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TECHNICAL REPORT 5009

BLAST CAPACITY EVALUATION OF SINGLE REVETTED BARRICADES

NORVAL DOBBS
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AMMANN & WHITNEY

PAUL PRICE
PICATINNY ARSENAL

NOVEMBER 1976

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A series of four explosive tests was performed to evaluate the blast resistant capacity of single revetted barricades when they are positioned close to explosions. Test results indicated that a typical earth-bermed cantilever wall barricade of the configuration tested will have a capacity to resist a maximum of 3,600 to 4,500 kg (8,000 to 10,000 lbs) of H.E. Further testing is needed to establish quantitative means for determining the capacity of barricades. Also, additional barricade designs should be developed for use with large quantities of explosives.

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ABSTRACT

A series of four explosive tests was performed to evaluate the blast resistant capacity of single revetted barricades when they are positioned close to explosions. Test results indicated that the typical earth-bermed cantilever wall barricade of the configuration tested will have a capacity to resist a maximum of 3,600 to 4,500 kg (8,000 to 10,000 lbs) of H.E. Further testing is needed to establish quantitative means for determining the capacity of barricades. Also, additional barricade designs should be developed for use with large quantities of explosives.

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SUMMARY

The Safety Manual, AMCR 385-100, requires that explosive manufacturing and loading plant buildings, which contain explosives and are separated at less than unbarricaded distances, be protected by single revetted earth-mounded barricades (earth-bermed walls). A protective barricade may be located at either the building containing hazards or at the building it is protecting. In case of an explosion within a building at which a barricade is located, the barrier may fail, depending upon the magnitude of the blast output associated with the explosion.

At the present time, the design of barricades is based upon the standards of the Safety Manual which do not provide quantitative means for determining the barricade's strength required to resist the effects of an explosion. In order to provide an insight into the blast-resistant capacities of earth-bermed walls, a series of tests was performed at Dugway Proving Ground under the direction of Picatinny Arsenal. This series consisted of four tests on two one-third scale models of a typical single revetted earth-mounded barricade. Three tests were performed on one of the models, whereas the second structure was subjected to the effects of only one explosion. The quantities of explosive (Composition C-4) involved in the first three tests (Wall No. 1) were 23 kg (50 lbs), 68 kg (150 lbs), and 113 kg (250 lbs), while the fourth test utilized a 227 kg (500 lbs) charge. Separation between the exposed surface of the reinforced concrete retaining wall and the center of the charge in each of the first three tests was 1.22 m (4 ft) while the separation distance used in the fourth test was 0.91 m (3 ft). Electronic instrumentation, as well as hand measurements, were used to determine the wall deflections. Also, both still and motion picture camera coverage was provided for documentation purposes.

The barricade used in the first three tests survived the combined effects of the three explosions; on the other hand, the structure failed in the final test. Based upon these results, it was estimated that the maximum blast-resistant capacity of a full-scale barricade of the configurations tested is in the order of 3,600 to 4,500 kg (8,000 to 10,000 lbs.)of H.E.

It is proposed that additional tests be performed to provide quantitative means for determining the blast-resistant capacity of single revetted earth-mounded barricades and to develop improved designs of barricade type structures for large explosive quantities.

INTRODUCTION

Background

Modern day explosive manufacturing and loading plants in many cases require the use of earth-mounded barricades in order to achieve safe separation between buildings. The Safety Manual, AMCR 385-100 (Ref 1), requires that single revetted barricades be positioned between two adjoining structures when these buildings are to be separated at less than the "unbarricaded intraline distance." However, presently there is no quantitative method to determine the maximum quantity of explosive which may be used with a given barricade. This allowable charge capacity is of significant importance particularly when the barricade is positioned close to a potential explosion.

In order to obtain data related to the performance, capacity and damage to single revetted barricades, a series of tests was undertaken by the Manufacturing Technology Directorate of Picatinny Arsenal, as part of its overall Safety Engineering Support Program for the U. S. Army Armament Command. This report, which was prepared with the assistance of Ammann & Whitney, Consulting Engineers, summarizes the results of these tests and provides conclusions and recommendations for further evaluation of earth-mounded walls.

Purpose and Objectives

The overall purpose of this test series was to provide an insight into the blast resistant capacities of earth-bermed reinforced concrete walls (single revetted barricades) when subjected to the close-in effects of H.E. explosions.

The objectives of the test program are summarized as follows:

1. To evaluate the strength afforded by both the reinforced concrete and the earth-mounded portions of the barricades.

2. To determine the modes of failure of single revetted walls when overloaded by blast.

3. To determine quantitatively the upper explosive limits of single revetted barricades.

Format and Scope of Report

This report is organized into three basic areas. The second section of the body of the report considers the test setups including a description of the test structures and the instrumentation. Damage sustained by the structures is described in the third section; while the conclusions based upon the test results, as well as the recommendations for further testing, are presented in the fourth section.

Since future standards of measurements in the United States will be based upon the SI Units (the International System of Units) rather than the United States System now in use, all measurements presented in this report will conform to that of the SI System. However, for those persons not fully familiar with the SI Units, United States equivalent units of particular test data are presented in parenthesis adjacent to the SI units. Also, a list of units, symbols, and United States conversion factors for SI units is presented in the Appendix.

TEST PROCEDURES

General

Four tests were performed at the White Sage Flat Test Facility range of Dugway Proving Ground (DPG) at Dugway, Utah, on February 23 through 25, 1976. This test series was the first of several series proposed in connection with the establishment of design criteria for barricades. Figure 1 illustrates the site layout of this test series.

Two earth-bermed walls were tested in connection with this series. One of the structures was subjected to three consecutive tests, whereas the other underwent only one test. In order to determine the structural response of the test structures, both electronic and hand measurements of the structural deflections produced by the blast were recorded. Photographic coverage of both pre- and post-shot conditions of each structure was made in order to define the damage incurred due to the blast.

Test Structures

Each structure consisted of a reinforced concrete wall and an earth-mound. The walls were designed as retaining walls for the earth-mound without additional reinforcement to resist the blast loadings. As will be shown, the size of each test structure was representative of a one-third scale model of a typical full-scale barricade.

Figure 2 illustrates the test structure after completion of construction while Figure 3 shows the structural details.

Each wall was 2.44 m (8 ft) high by 4.88 m (16 ft) long and 0.25 m (10 in.) thick. Support for each wall was provided by a 1.78 m (5 ft-10 in.) long reinforced concrete slab which was cast monolithically with the wall. The slab had a concrete thickness of 0.31 m (1 ft). Both the wall and the slab were reinforced with No. 3 bars positioned 0.2 m (8 in.) on center and in both directions (Fig 3). To simulate the concrete floor slab of an adjoining building a 0.15 m (6 in.) thick concrete slab was poured adjacent to, but not monolithic with, the foundation slab of the wall. This slab produced the reflections of the blast wave which could be expected to be associated with an explosion in a building located immediately adjacent to a barricade.

Located to the rear of each wall was an earth-mound; the shape of which conformed to the requirements of AMCR 385-100.

The height of the mound was equal to that of the wall. Adjacent to the wall the earth-mound consisted of a 0.91 m (3 ft) flat section, which then tapered to the ground on a 2 to 1 slope. Although the 0.91 m wide section of the mound conformed to the requirements of AMCR 385-100 for barricades having heights of 6.1 m (20 ft) or less, this dimension was selected based upon the criterion developed for this project which recommends that for future construction the width of the full height section of mound adjacent to the wall should be at least equal to one-third the wall height. The soil throughout the mound was compacted to 92 percent of the maximum dry density in accordance with Reference 2.

Figure 4 illustrates the construction phase of the walls; while Figure 5 is a rear view of the earth-mound at completion of construction. Reference 3 presents additional phorographs of the construction phase of the program.

Instrumentation and Measurements

Deflection Gages

Wall No. 1 was provided with six electronic deflection gages. Five gages were used to measure the deflection/time history of the wall movement while the sixth gage recorded the movement of the foundation slab. All six gages were linear displacement transducers which operated on the principle of change in inductance in the coils of a linear differential transformer with change in position of the core. These gages had a 0.15 m (6 in.) stroke which, as will be discussed later, was exceeded in several of the tests.

Each gage was mounted at the mound side of the structure on steel support frames. The deflection rods (cores) were connected to steel rods (Fig 6) which passed through pipe sleeves. The steel rods were attached rigidly to the back side of the walls. Movement of the wall caused the deflection rods to move within the gage. The sleeves minimized any binding of the steel rods by the compacted earth (Fig 7).

A layout of the deflection gages and associated equipment is presented in Figure 8, while the location of the steel rod attachment points to the wall is illustrated in Figure 9.

Hand Measurements

Other measurements of the wall movements were made by hand. Here, the pre-shot measurements of selected points (Fig 10) on

the wall surface relative to fixed reference stations were made. After the test, similar measurements were made, with the difference between the two sets of measurements indicating the permanent movement of the structure. As will be shown later, the hand measurements agreed favorably with the permanent displacement obtained from the electronic instrumentation.

Streak Camera Measurements

A streak camera was also used to determine wall displacements. Here, one light was attached to the deflection rod while the second light was attached to the deflection gage support. The movement of the light on the rod relative to the fixed light on the support was recorded by the streak camera.

Mountings for both the fixed and movable lights are illustrated in Figure 11.

Photographic Documentation

Pre- and post-test conditions of the walls were recorded by still photography. Also, 16 mm motion pictures of the detonation and resulting wall damage were taken. Two motion picture cameras were used; each having a speed of approximately 3,000 frames per second. Unfortunately the speeds of these cameras were so fast that only the fireball and resulting smoke was recorded. Future tests should consider the use of much slower cameras to photograph fragment debris which would occur at a later time.

Test Setup

As previously mentioned, Wall No. 1 was tested three times whereas only one test was performed on Wall No. 2.

The explosive used in all four tests was Composition C-4. The individual charges consisted of a series of C-4 blocks, each weighing approximately 0.6 kg (1-1/4 lbs). Except for Test No. 1, the individual charges were arranged to form a cubicle shape. The charge of Test No. 1 had a height equal to approximately one-half the size of either dimension of the base. All charges were initiated electrically from the control house.

The weights of the individual charges used in the various tests are given below:

Test No. 1	-	23 kg	(50 lbs)
Test No. 2	-	68 kg	(150 lbs)
Test No. 3	-	113 kg	(250 lbs)
Test No. 4	-	227 kg	(500 lbs)

The individual charges were supported on wooden benches. The height of the center of each charge was 1.22 m (4 ft) above the concrete pad in front of the wall. Except for Test No. 4, the center of each charge was positioned 1.22 m (4 ft) from the face of the wall. In the last test, the separation distance used was 0.91 m (3 ft). This decrease in stand-off distance contributed substantially to the structure's damage.

If the test structures are considered to be one-third scale models, then the equivalent full scale charge weights and stand-off distances for the four tests would be:

Test No.	Equiv. Charge Wt. (kg)	Equiv. Stand-off Distance (m)
1	612 (1,350 lbs)	3.66 (12 ft)
2	1,837 (4,050 lbs)	3.66 (12 ft)
3	3,062 (6,750 lbs)	3.66 (12 ft)
4	6,120 (13,500 lbs)	2.74 (9 ft)

TEST RESULTS

General

Crack patterns, and displacement measurements are used to present the test results. The photos and crack patterns illustrate the damage sustained by the various wall elements, whereas the displacement measurements indicate the motions to which the walls were subjected. Both permanent and time dependent displacements are presented. Because of the severe damage sustained by Wall No. 2 in Test 4, the results of this latter test is only presented in pictorial form.

Structural Damage

Test Number 1

The damage sustained by Wall No. 1 was relatively minor (Fig 12). A small portion of the wall immediately in front of the explosion (see Figure 2 for test setup) was spalled to a depth of approximately 0.8 mm (1/32-in.). Minor hairline cracks were formed at the intersection of the top of the haunch and wall (Fig 13). Formation of these cracks indicated that the center of the wall settled relative to both ends. This settlement was attributed to the high reflected pressures produced on the floor slab immediately in front of the explosive.

Figure 12 illustrates the concrete spalling of the wall. The dark area around the spalling is attributed to the scorching of the concrete paint by the fireball. Also shown in this photo is the size of the crater formed in the non-monolithic portion of the slab. The depth of the crater did not extend the full depth of the slab. In addition to the crater formation, the non-monolithic slab was depressed downward by the blast, a greater amount than was the portion of the slab which was cast monolithic with the wall. Here, the non-monolithic slab merely acted as a slab on an elastic foundation, whereas the interaction between the monolithic slab and wall tended to span the slab loads across the wall as a beam. In actual construction, advantage should be taken of this beam action of the wall in order to reduce the overall slab depressions.

It was expected that a considerable amount of damage would be sustained by the sandbags and the wood support frames for the sides of the earth-mound. As can be seen from Figure 14 the damage was minimal, with only a few of the front (facing the blast) sandbags being damaged. Damage to the sandbags permitted the plywood paneling of the frames to be displaced away from both

ends of wall by approximately 13 mm (1/2 in.).

Test Number 2

The pre-shot setup for Test No. 2 is shown in Figure 14. It may be noted that a steel plate cover was placed over the crater formed in Test No. 1 in order to insure stability of the wooden bench supporting the explosive charge prior to testing.

Both the spalling and cracking damage sustained by the wall in the first test was appreciably increased in this test (Fig 15). The area of the spalled section was increased to cover approximately one-third of the wall area. The depth of the spall was increased to 1.6 mm (1/16 in.). Cracks as large as 6.4 mm (1/4 in.) in width were formed radially around the spalled area (Fig 16). This formation of tension cracks at the quarter points along the length of the wall indicated that the center of the wall deflected into the soil a larger amount than did the edges. However, the relative magnitude of these displacements indicated that a considerably amount of the blast load acting on the central portion of the wall was distributed to the wall edges by soil behind the wall.

Cracks formed at the intersection of the wall and the haunch along the mid-section of the wall were of such a agnitude to produce failure at this section of the vertical reinforcement. If the mound had not been behind the wall, the remainder of the reinforcement at the haunch would have probably failed, thereby resulting in wall disengagement. It may be noted in Figure 16, that additional tension cracks were formed at the two lower corners of the walls. These cracks are a continuation of the crack formed by the above mentioned reinforcement failure.

Damage to the sandbags and wood frame was slightly increased from that of the first test (Fig 17). However, the integrity of the mound and its supports was still essentially intact.

Test Number 3

This test was the third and last in a series of tests of Wall No. 1. The explosive quantity involved was 113 kg (250 lbs). The crater in the floor slab produced in the first two tests was covered with a steel plate to minimize enlargement of the crater (Fig 18).

Cratering of the concrete occurred near the center of the wall (Fig 19). The depth of the crater penetrated beyond the depth of the nearside reinforcement, but did not penetrate the

entire wall depth. Reinforcement was exposed over the middle one-quarter of the wall. The cratering was a result of the high concentrated impulse loads produced immediately in front of the charge and the dispersal of the soil in back of the upper 0.6 m (2 ft) of the wall (Fig 20). This soil displacement minimized the load distribution thereby creating the relatively large wall displacements. If laced reinforced concrete (Ref 4) had been used in place of standard reinforced concrete, the size of the crater would have been less pronounced.

Severe cracking, as large as 25 mm (1 in.), was formed adjacent to the crater (Fig 21). The formation of these cracks was a result of the tension forces produced by the large differential motions between the center and edges of the wall. These cracks were an extension of the cracks formed in Test No. 2.

Cracks which were associated with reinforcement failure at the base of the wall extended across the middle 75 percent of the wall base. Cracks as large as 38 mm (1-1/2 in.) were formed midway between the wall base (at the haunch) and the bottom of the crater. These latter cracks were formed as a result of the high compaction of the soil behind the base wall as compared to that of the soil behind the upper regions of the wall.

Although the concrete wall was severely cratered, the damage to the earth-mound was considered to be minimal. The separations between the earth-mound and the plywood supports were slightly increased above those of the first two tests. However, these separations did not endanger the stability of the mound. As was mentioned, the soil behind the upper part of the wall was displaced thereby leaving the upper 0.51 m (2 ft) of the wall without support from the soil. This situation resulted in small sections of the top of the wall being disengaged from the wall proper. This latter situation can be rectified in a barricade design by assuring that the necessary soil compaction is maintained at the top of the wall, and the top of the concrete is reinforced with U-bars.

Test Number 4

Test No. 4 was the only test performed on Wall No. 2 (Fig 22). Total quantity of explosive involved was 227 kg (500 lbs). The overall results of this test indicated that partial failure of the wall occurred.

Significant damage was sustained by the wall. The center one-third of the wall was completely destroyed (Fig 23) with the blast pressures penetrating through the earth-mound. The

remainder of the wall (Fig 24) received no more damage than what was received by the Wall No. 1 after the completion of the first three tests.

Debris resulting from the breakup of the wall at the center was dispersed approximately 100 m (330 ft) to the rear of the barricade. The size of the fragments were such as to create a hazardous situation for structures which would be located within intraline distances of the barricade.

Figure 25 illustrates the debris formed from the wall breakup.

Deflection Measurements

Hand Measurements

Post-shot permanent deflection patterns of the wall after each of the first three tests were obtained by hand measurements and are illustrated in Figures 26 through 28. The deflections given in each of the three patterns are relative values; e.g. the values given in the deflection patterns for Test No. 3 are equal to the total permanent deflection of the wall minus the permanent deflection of the wall sustained in Test No. 2. Relative deflections were used rather than total deflection in order that the magnitude of the permanent deflections obtained by hand could readily be compared with the permanent deflections obtained from the electronic gage measurements. Also, the relative deflections provide a direct measurement of the energy absorbed by the wall in a given test.

The patterns of deflections occurring in all three tests were similar except, as may be expected, their magnitudes differed. The deflections near the center of the wall, adjacent to the charge, were relatively large compared to the displacements near the wall edges. This deflection variation with location resulted in an appreciable change in the surface curvature. This curvature change was most pronounced at about one meter (3 ft) from each side of the vertical center line of the wall where the large concrete cracks were located. Large angles of rotation up to 18 degrees were associated with this curvature change.

Deflections at the bottom of the wall (top of the haunch) were relatively small due to the presence of the base slab which served as a support beam to restrain horizontal movement at the middle of the wall in comparison to those at the edges. Also, the soil resistance was maximum at the bottom of the wall thereby adding to the overall strength of this section of the wall to resist

movement. For the two lower corners of the wall, it may be noted that their displacements increased between the first and second tests, but then decreased between Test Nos. 2 and 3. This reversal in deflection is attributed to severe cracking at the points of curvature which occurred during Test No. 3.

Deflections at the upper two corners were also relatively small. The blast loads acting on these portions of the wall were low compared to those at the center of the wall and, therefore, the compacted soil behind the corners tended to serve as supports to resist motion of the top central part of the wall.

As in the case of the wall, the maximum displacement occurred at the center of the floor slab which was cast monolithically with the wall. Here, the increased deflection at the center of the slab in Test No. 3 was four times as large as the corresponding deflection in Test No. 1, while the deflections at the ends of the slab in the two tests differed only by ratios of two to three (varied for each end).

Deflection Gage Measurements

A summary of the maximum and permanent relative deflections recorded by each gage in each of the first three tests are listed in Table 1, whereas the deflection-time histories are illustrated in Figures 29 through 36. For comparison the magnitudes of all recorded deflections have been presented both in the metric and U. S. units.

As may be seen, the maximum deflections varied anywhere from two to six and one-half times their corresponding permanent deflections. This large differential was attributed primarily to the elastic rebound of the earth-fill. If the earth-fill were not present, the magnitudes of the maximum displacements of the wall would only be slightly larger than those of the permanent deflections. The large rebound of the earth is indicative of the great strength afforded to the system (wall and soil) by the soil in resisting the blast overpressures.

It may be noted from Table 2 that the permanent deflections obtained from the gage measurements compare very favorably with those of the hand measurements.

Evaluation of Test Results

The single charge capacity of Wall No. 1 was definitely greater than 113 kg (250 lbs) used in Test No. 3, but was probably smaller than 204 kg (450 lbs) which is equal to the sum of

the explosive charges used in the first three tests. The rebound afforded by the soil during each test was significant; and thereby limited the magnitude of the permanent deflection of the wall after any one test. That is to say, the sum of the permanent displacements obtained from the individual tests would have been less than that produced by the combined weight of the explosive of 204 kg. In the latter case, the initial velocity of the wall might have been of sufficient magnitude to overpower the resisting capacity of the system (concrete and soil), and thereby produce soil displacements large enough to make the wall fail. This overpowering of the system was demonstrated in Test No. 4 where the damage sustained by Wall No. 2 can be considered as a structural failure.

Based upon the above, it can be concluded that a full scale single revetted barricade having dimensions equal to three times those of the test structure, would have an upper explosive limit somewhere in the order of 3,600 to 4,500 kg ($\approx$8,000 to 10,000 lbs) of H.E. when a minimum separation between the retaining wall and the center of a single charge is at least 3.66 m (12 ft). For separation distances less than 3.66 m, the explosive limit of the wall is less than that stated. Also, if the enclosure of the explosive results in reflective surfaces or confinement greater than that produced by a single barricade (barricades on two or more sides of the explosive), then the amplification of the blast loads due to multiple reflections of the blast output will reduce the explosive limit. On the other hand, if the charge is distributed into several smaller charges, rather than being concentrated as in these tests, then either the charge capacity will increase for a given separation distance or the safe separation distance will decrease for a given total explosive quantity. This latter situation is true because of the more effective use made of the soil along the entire length of the wall.

Comparison of Test Results with Existing Facilities

Many existing and newly designed facilities have utilized single revetted barricades located at potentially donor structures to reduce safe separation between buildings. However, the design of these barricades only considered the structural requirements needed for conventional stability without giving consideration to the blast effects associated with an explosion. The following examples illustrate the need for design criteria whereby the explosive limits of the barricades can be determined.

Radford AAP TNT Line Accident

An accidental detonation took place in the Nitration and Purification Building (Building 9502) in Line A of the TNT Manu-

facturing Facility at Radford AAP. At the time of the incident, the quantity of explosive contained in the building was estimated to be equivalent to 3,630 kg to 5,440 kg (8,000 to 12,000 lbs) of TNT.

Building 9502 was a partially belowground structure; the aboveground portion was barricaded on all four sides by an earth-mounded barricade (Fig 37). The earth-mound, as well as the earth around the belowground portion of the structure (Fig 38) were supported by reinforced concrete walls. The intersecting walls formed the rectangular shaped structure having plan dimensions of 19.51 m (64 ft) by 17.37 m (57 ft). The overall height of the building was 9.14 m (30 ft). The aboveground barricaded portion was 3.96 m (13 ft) high. The barricade was flat on the top for a width of 0.91 m (3 ft), and sloped downward on approximately 1:1-1/2 slope providing overall width of the barricade of 6.70 m (22 ft). The thickness of the supporting walls was 0.31 m (1 ft).

The total building was destroyed (Fig 39) with only a crater remaining after the explosion. Equipment and the concrete retaining wall fragments, some of which as large as 23 kg (50 lbs), were found as far away as 915 m (3,000 ft).

The results of this accident were similar to the results of Test No. 4. Although the quantity of explosive in Building 9502 was slightly less than that of the full scale version of the test structure, the confinement of the explosion produced by the continuity of the barricade around the building, as well as the confinement produced by a portion of the structure being positioned below the grade, enhanced the blast output and destroyed the building. Another possible contributing factor leading to the destruction of the building was the relatively thin walls which varied in thickness from 0.56 m (1 ft-10 in.) at the floor slab to 0.3 m (1 ft) at the roof. Here, the blast pressures probably penetrated the concrete in front of the explosions and the soil behind the wall and dispersed the soil and concrete away from the buildings. The point of blast penetration probably propagated along the wall until the wall completely failed.

Lone Star AAP 105 mm Projectile Melt/Pour Facility

The 105 mm Projectile Melt/Pour Facility at Lone Star AAP is presently being modernized to reduce production costs and achieve increased safety of operation. This facility utilizes the continuous explosive melting process as developed by Picatinny Arsenal. Two continuous melters are needed to achieve the required production rate.

Each melter is housed in an individual two-story building. The lower portion of the structure is constructed below the ground whereas the upper level, located above the grade, is protected from explosions in the adjoining buildings by single revetted barricades on three sides and by a laced reinforced concrete wall on the fourth side. The height above the ground of the barricade and wall is approximately equal to the wall height of the full scale version of the test structure.

Figures 40 and 41 illustrate the plan layout and vertical section of each of the melt/pour buildings.

Each structure was designed for an explosive quantity, within the building, of 1,134 kg (2,500 lbs) of TNT. Although the building is enclosed on all four sides, the quantity of explosive involved is much less than that of the full scale structure test of Wall No. 2. Therefore, in the event of an explosion in this building, it may be expected that the barricades will survive the effects of the blast output without failure.

Belowground Structure Tests

In conjunction with this series of tests, a second series of explosion tests was performed to evaluate the blast resistant capacities of structures which are positioned below the grade (Ref 6). The results of this second series seem to verify the previously stated results of this study that if a building is barricaded at all four sides, the barricade will have a smaller explosive charge weight capacity than if the structure were barricaded at only one side (cantilever barricade). To illustrate this feature let us consider the setup and results of the belowground test series described below.

Cell No. 2 of the belowground tests was a reinforced concrete cubicle without the roof (Fig 42) with the inside dimension of each side being 2.18 m (8 ft). Located at the top of the walls was a 0.91 m (3 ft) wide by 0.20 m (8 in.) thick reinforced concrete apron which provided increased support for the top of the walls.

The structure was tested twice, first with an explosive charge of 87 kg (190 lbs), and the second time with a 113 kg (250 lbs) charge. Both charges were positioned at the center of the structure.

After completion of the second test, the cell was completely destroyed with two of the four walls disengaged and dispersed as debris, and the remaining walls severely damaged. Although the

earth-bermed Wall No. 2 of the barricade tests was considered also to have failed, the damage to the cell of the belowground series was extensively more severe than that of the barricade test. This greater damage occurred even though the charge weight was larger and the separation distance was smaller in the barricade test than in the cell test. Therefore, this greater damage has been attributed to the increased blast effect produced by the confinement of the explosion by the four walls of the cell.

Another factor for the increased damage may have been the concrete thickness of the cell walls which was less than that of the earth-bermed wall. The high blast pressures produced on the wall immediately in front of the explosion developed extremely large shear forces which failed the thinner concrete sections more readily. This local failure or cratering of the concrete permitted the blast to disperse the supporting soil from behind the wall and thereby further weakened the structure until overall collapse occurred. This total failure occurred notwithstanding the concrete, in combination with the supporting soil, had sufficient strength to resist the blast by "plate action."

Therefore, in order for a barricade to resist the effects of an explosion, it must have adequate strength to resist not only the blast output as a unit, but also to resist the formation of concrete craters by high local blast pressures.

Figure 43 illustrates the above mentioned overall damage to the structure. It may be noted that in addition to the destruction of two walls, the concrete apron at the top of the walls was also destroyed.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results of these tests indicate that when subjected to close-in effects of a detonation, an earth-mounded single revetted barricade conforming to the standards of AMCR 385-100 will have upper explosive limits beyond which the barricade will fail. For a cantilever type barricade which has overall dimensions equal to three times those of each test structure, this upper explosive limit will be in the order of 3,600 to 4,500 kg (≈8,000 to 10,000 lbs) of H.E. when a minimum separation of 3.67 m (12 ft) is maintained between the barricade and the center of a single charge. For separation distances less than 3.67 m, the upper explosive limit will be less. Also, if the enclosure of the explosive results in reflective surfaces or confinement of the blast greater than that produced by the single (cantilever) barricade, the upper explosive limit will be further reduced. In addition, the upper explosive limit of a barricade may be reduced if a local failure (or cratering) of the concrete portion of the structure is not negated.

Recommendations

It is recommended that additional tests be performed to determine quantitative criteria for the design of revetted barricades and to develop improved designs of barricade type structures for large explosive quantities.

REFERENCES

1. "Safety Manual", AMC Regulation AMCR 385-100, Headquarters, U. S. Army Materiel Command, Washington, D.C., April 1970 (with 14 October 1971 and 12 September 1974 changes)

2. "Moisture-Density Relations of Soils Using 10-lb (4.5 kg) Hammer and 18-in. (457-mm) Drop", ASTM Designation D 1557-70, Annual Book of ASTM Standards, 1975

3. Warnecke, C.H., "Support Test for Earth-Bermed Donor Wall," Document No. DPG-DR-C977A U. S. Army Dugway Proving Ground, Dugway, Utah, May 1976

4. "Structures to Resist the Effects of Accidental Explosions, (with Addenda)", TM 5-1300/NAVFAC P-397/AFM 88-22, Department of the Army, the Navy, and the Air Force, Washington, D.C., June 1969

5. "Overpressure Effects on Structures," HNDTR-75-23-ED-SR, U. S. Army Corps of Engineers, Huntsville Division, 1 February 1976

6. "Blast Capacity Evaluation of Belowground Structures," Manufacturing Technology Directorate, Picatinny Arsenal, Dover, New Jersey (in preparation, scheduled for publication in early 1977)

Table 1

Summary of deflections

Test Number	Gage Number	Maximum Deflection mm	Maximum Deflection (in.)	Permanent Deflection mm	Permanent Deflection (in.)
1	1	16	(0.63)	2	(0.08)
	2		(a)		(a)
	3	12	(0.47)	4	(0.16)
	4	13	(0.51)	9	(0.35)
	5	23	(0.91)	9	(0.35)
	6	14	(0.56)	8	(0.32)
2	1	110	(4.33)	18	(0.71)
	2	91	(3.58)	46	(1.81)
	3	44	(1.75)	17	(0.67)
	4		(a)		(a)
	5	26	(1.03)	8	(0.31)
	6	48	(1.89)	34	(1.33)
3	1	114	(4.50)		(b)
	2		(c)		(c)
	3	56	(2.20)	28	(1.10)
	4		(c)		(c)
	5		(a)		(a)
	6		(c)		(c)

[a]Deflection fixture disconnected.

[b]Maximum travel beyond capacity of gage.

[c]Gage not used.

Table 2

Comparison of gage and hand measurements

Test Number	Gage Number	Permanent Deflection, mm (in.) Hand Meas.[a]		Gage		Remarks
1	1	2	(0.09)	2	(0.08)	
	2	7	(0.27)		(b)	
	3	5	(0.19)	4	(0.16)	
	4	≈12	(0.47)	9	(0.35)	
	5		(c)	9	(0.35)	
	6	7	(0.27)	8	(0.32)	0.03 in. deep spall
2	1	13	(0.50)	18	(0.71)	
	2	55	(2.14)	46	(1.81)	
	3	14	(0.55)	17	(0.67)	
	4	≈84	(3.27)		(b)	0.06 in. deep spall
	5		(c)	8	(0.31)	
	6	30	(1.17)	34	(1.33)	0.06 in. deep spall
3	1	35	(1.38)	63	(2.48)	
	2	≈130	(5.0)		(d)	spalling of surface
	3	25	(1.00)	28	(1.10)	
	4	≈360	(14.2)		(d)	hand measurement behind reinf.
	5		(c)		(b)	
	6	≈70	(2.75)		(d)	

[a] Hand measurements can vary by ±1 mm.

[b] Deflection fixture disconnected.

[c] No hand measurements made.

[d] Gage not used.

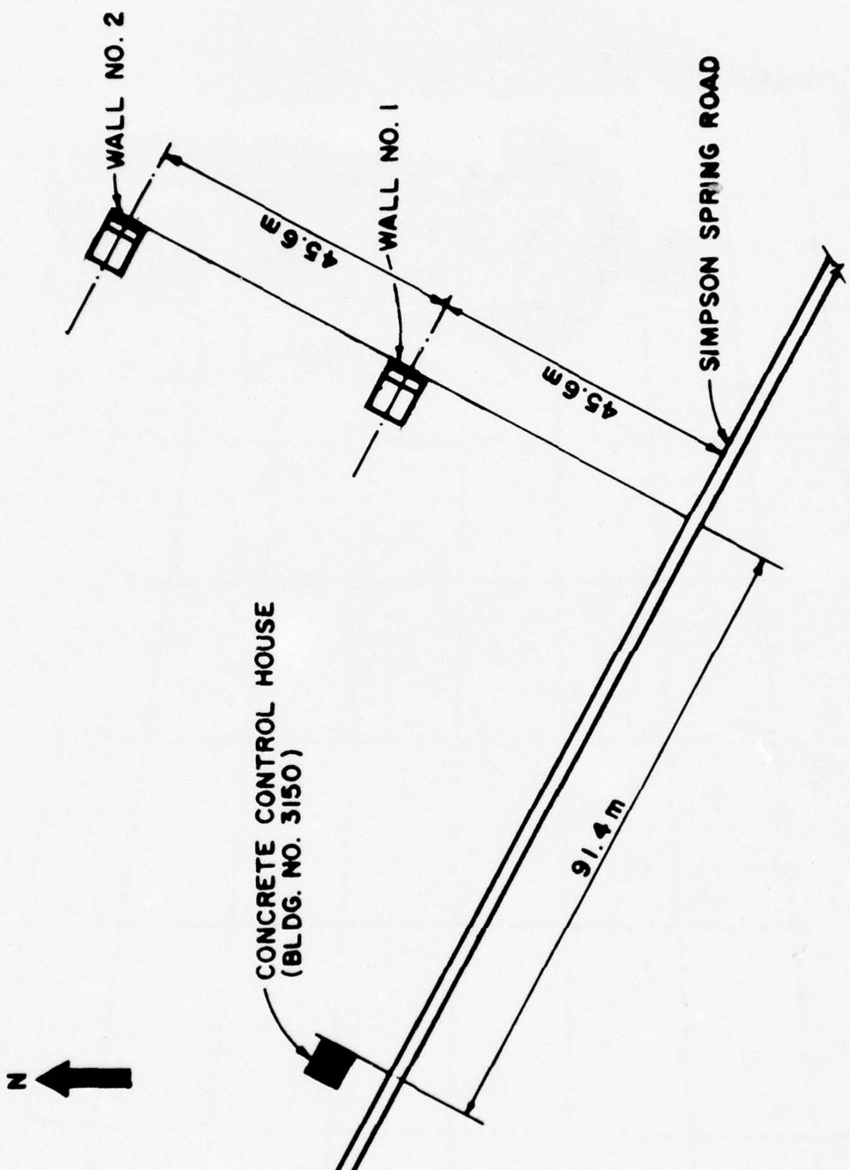


Fig 1 White Sage Flat Test Site

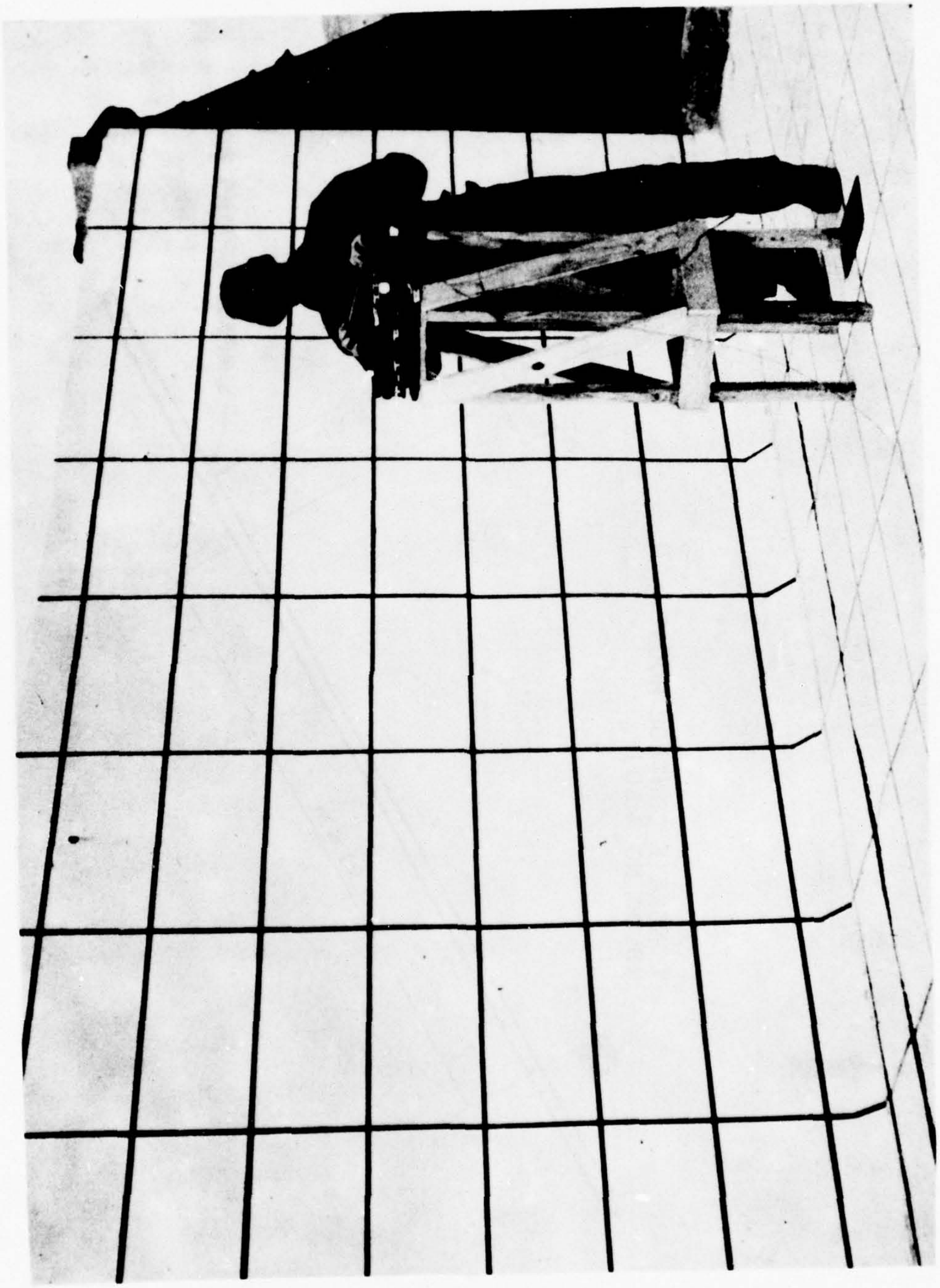


Fig 2 Test structure

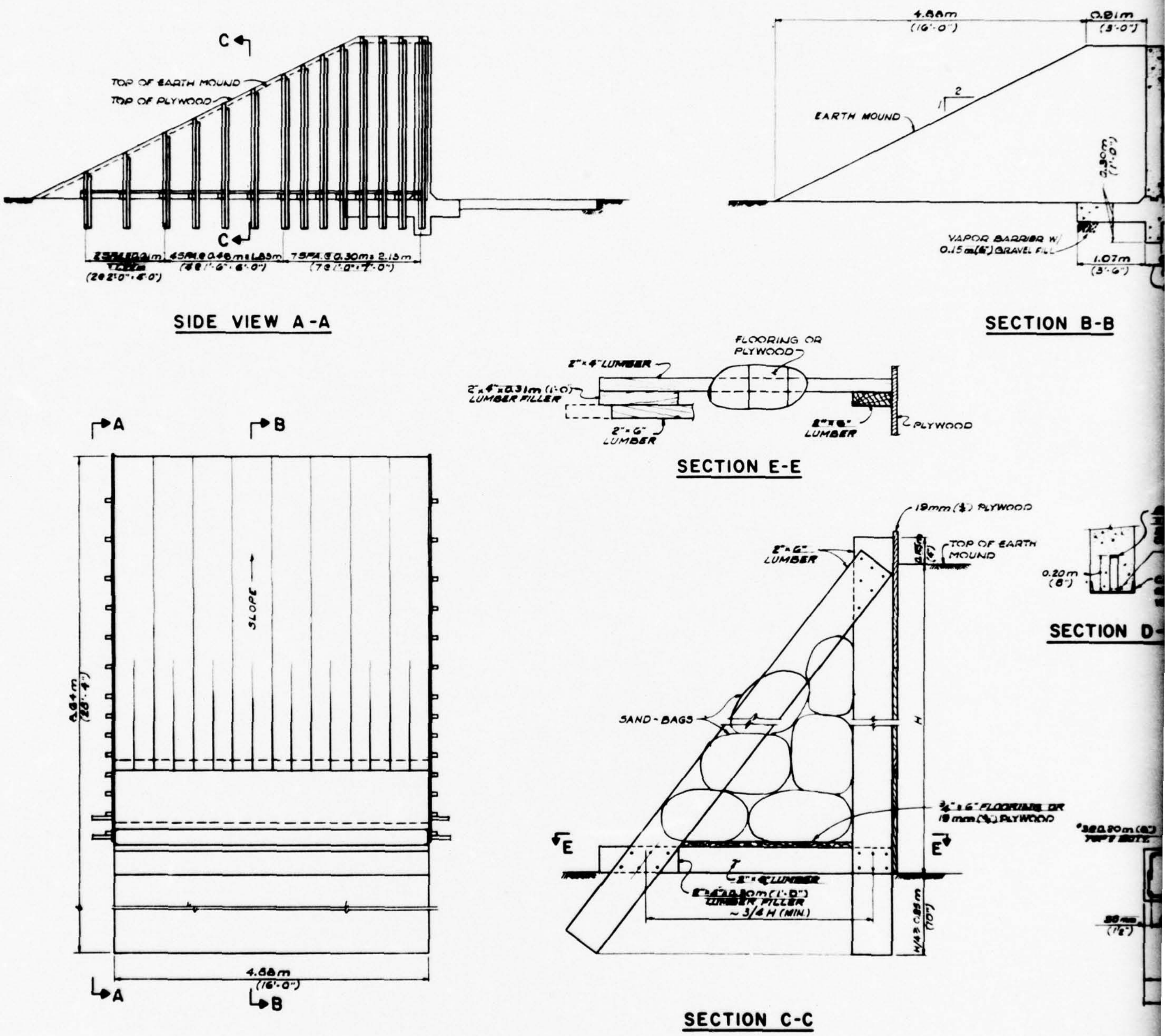
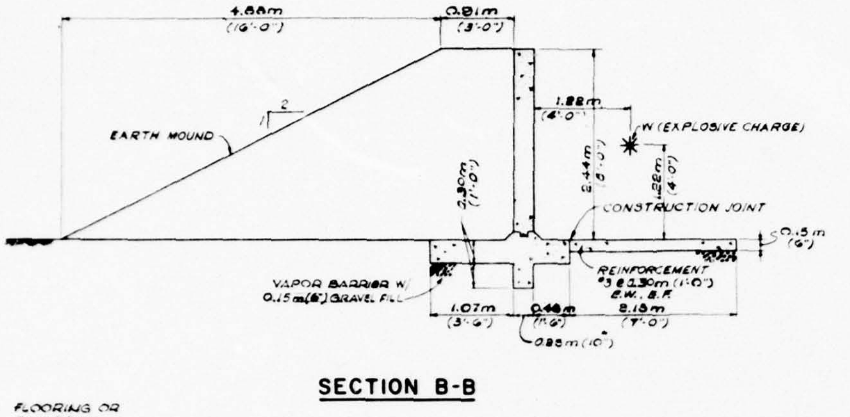
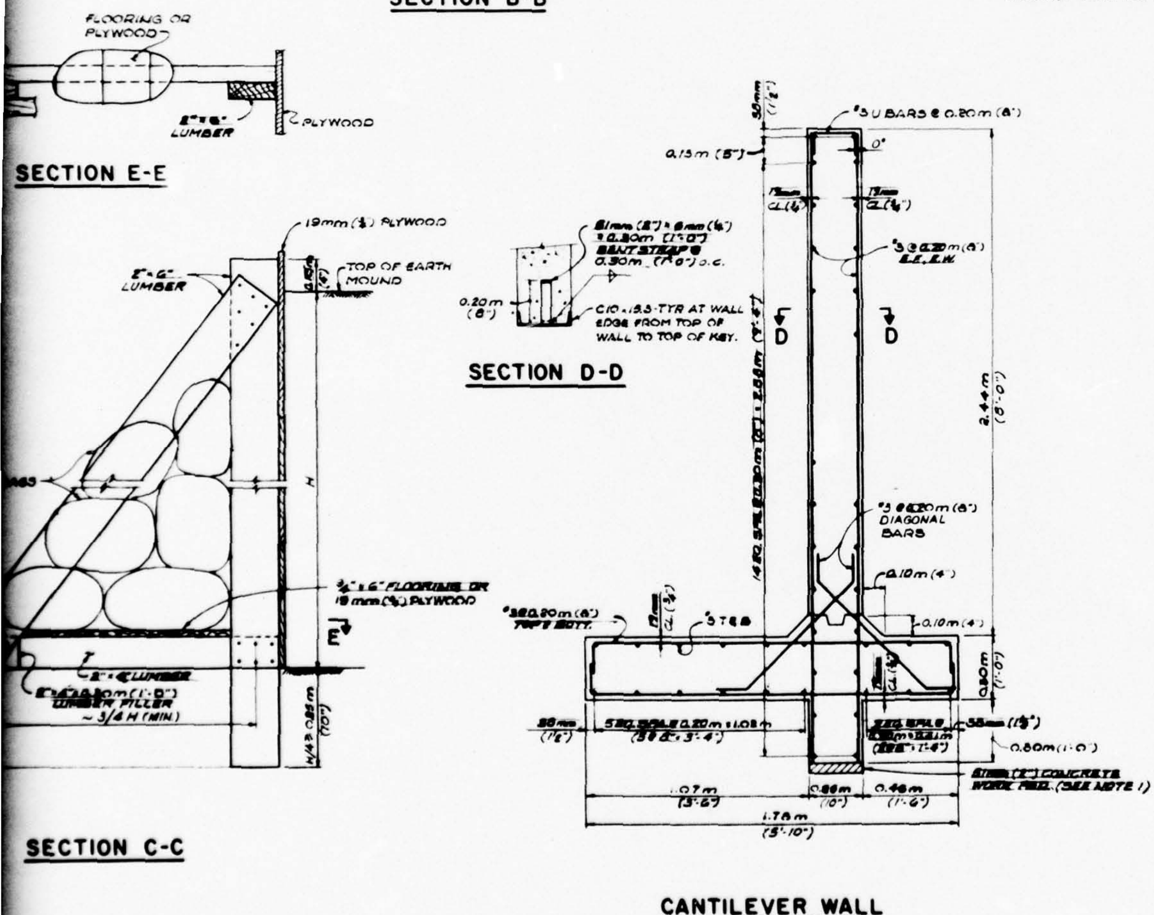


Fig 3 Structural details



NOTES:

1. CONCRETE FOR THE 51mm (2") CONCRETE WORK PAD UNDER WALL; f'_c = 13.79MPa (2,000psi). CONCRETE FOR ALL OTHER CONSTRUCTION; f'_c = 27.58MPa (4,000psi).
2. All REINFORCING BARS SHALL CONFORM TO SPECIFICATIONS FOR DEFORMED STEEL BARS. ASTM DESIGNATION A615, GRADE 60.
3. AFTER REMOVAL OF FORMWORK & ADEQUATE CURING OF CONCRETE, FORM BACKFILL MOUND USING WELL GRADED SAND-GRAVEL MATERIAL WITH A MAXIMUM PARTICLE SIZE OF 51mm (2in). THE BACKFILL MATERIAL SHALL HAVE AT LEAST 10% RETAINED ON THE #4 SIEVE AND NOT MORE THAN 10% PASSING THE #200 SIEVE.
4. BACKFILL SHALL BE PLACED IN LOOSE LAYERS NOT MORE THAN 0.20m (8in.) IN THICKNESS AND COMPACTED TO AT LEAST 92% OF MAXIMUM DRY DENSITY AS DETERMINED BY ASTM D-1557.
5. BACKFILL OPERATION SHALL BE COORDINATED WITH PLACEMENT OF INSTRUMENTATION FOR THE TEST.
6. PROVIDE GREASE ALONG 19mm (3/4") PLYWOOD WHICH IS IN CONTACT WITH THE WALL.



g 3 Structural details

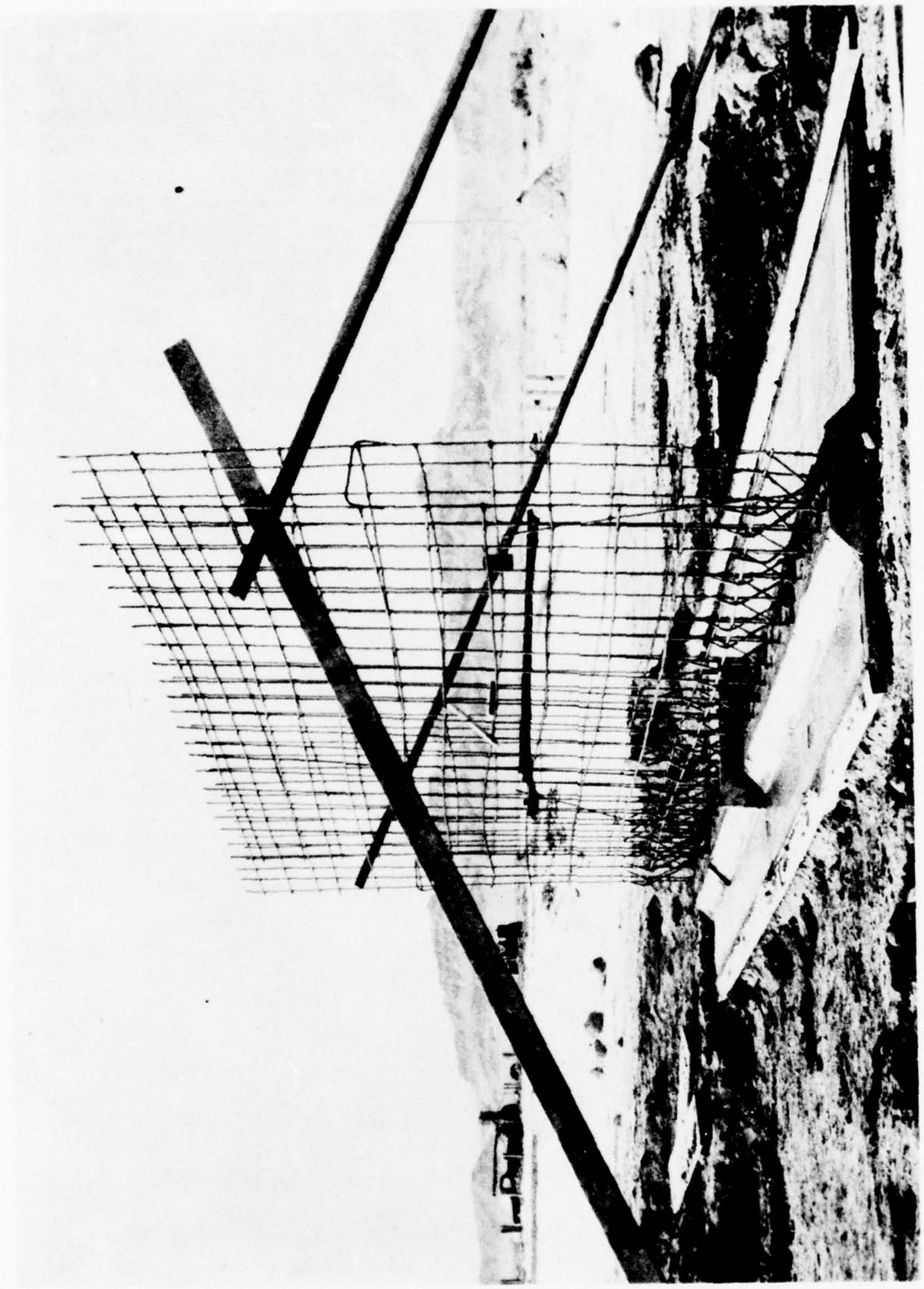


Fig 4 Construction phase

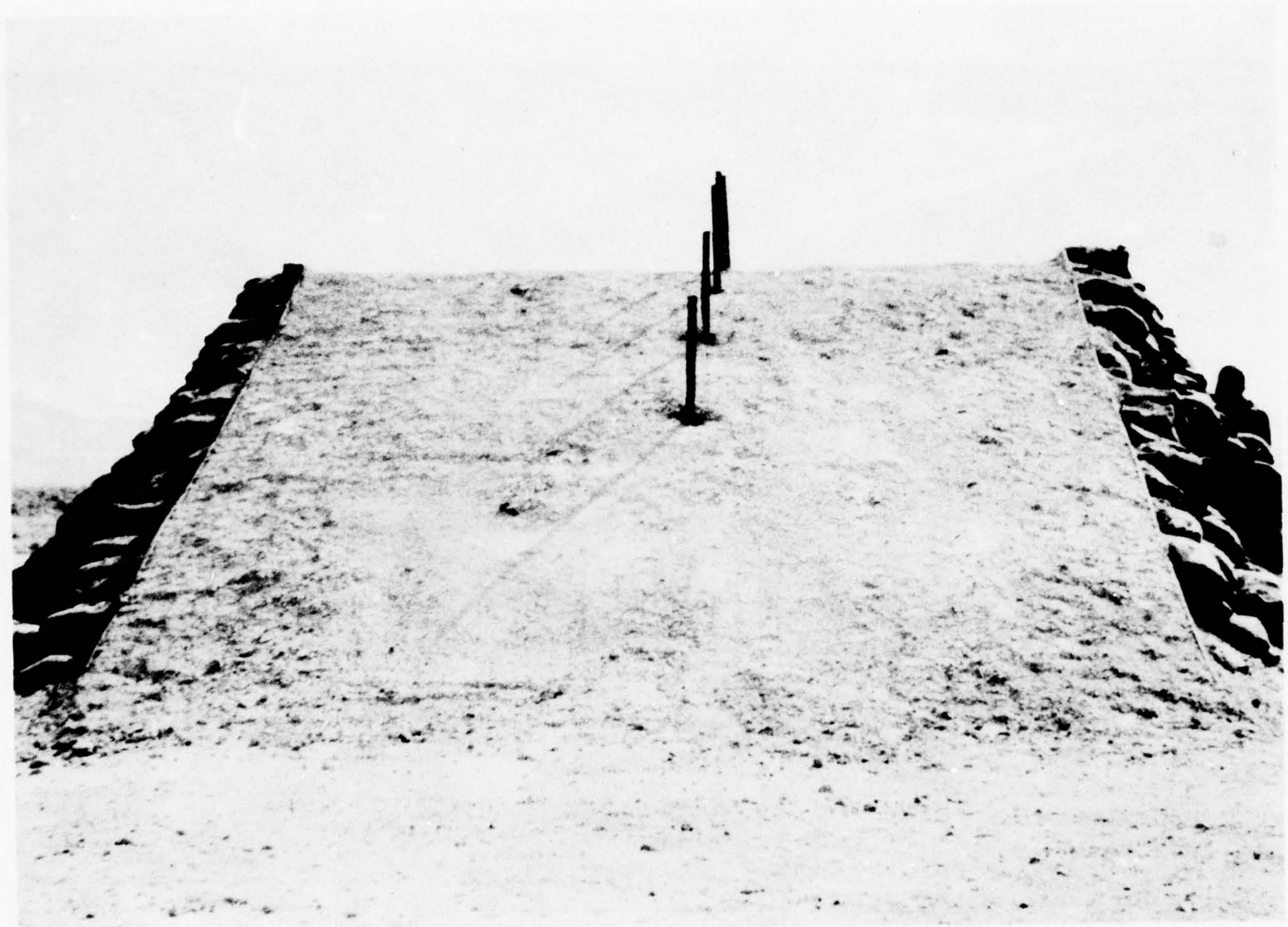


Fig 5 Earth-mound

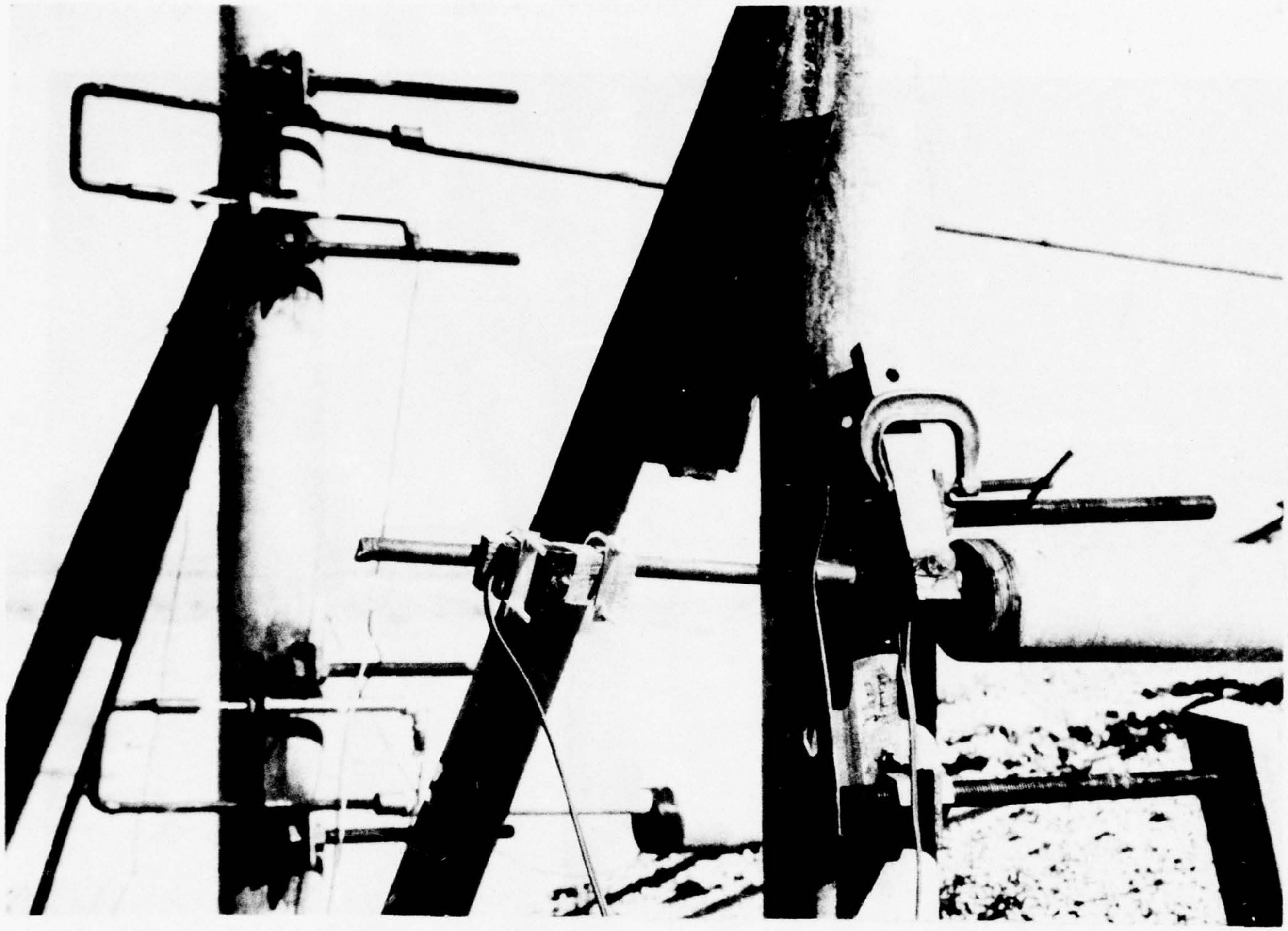


Fig 6   Deflection gage and support

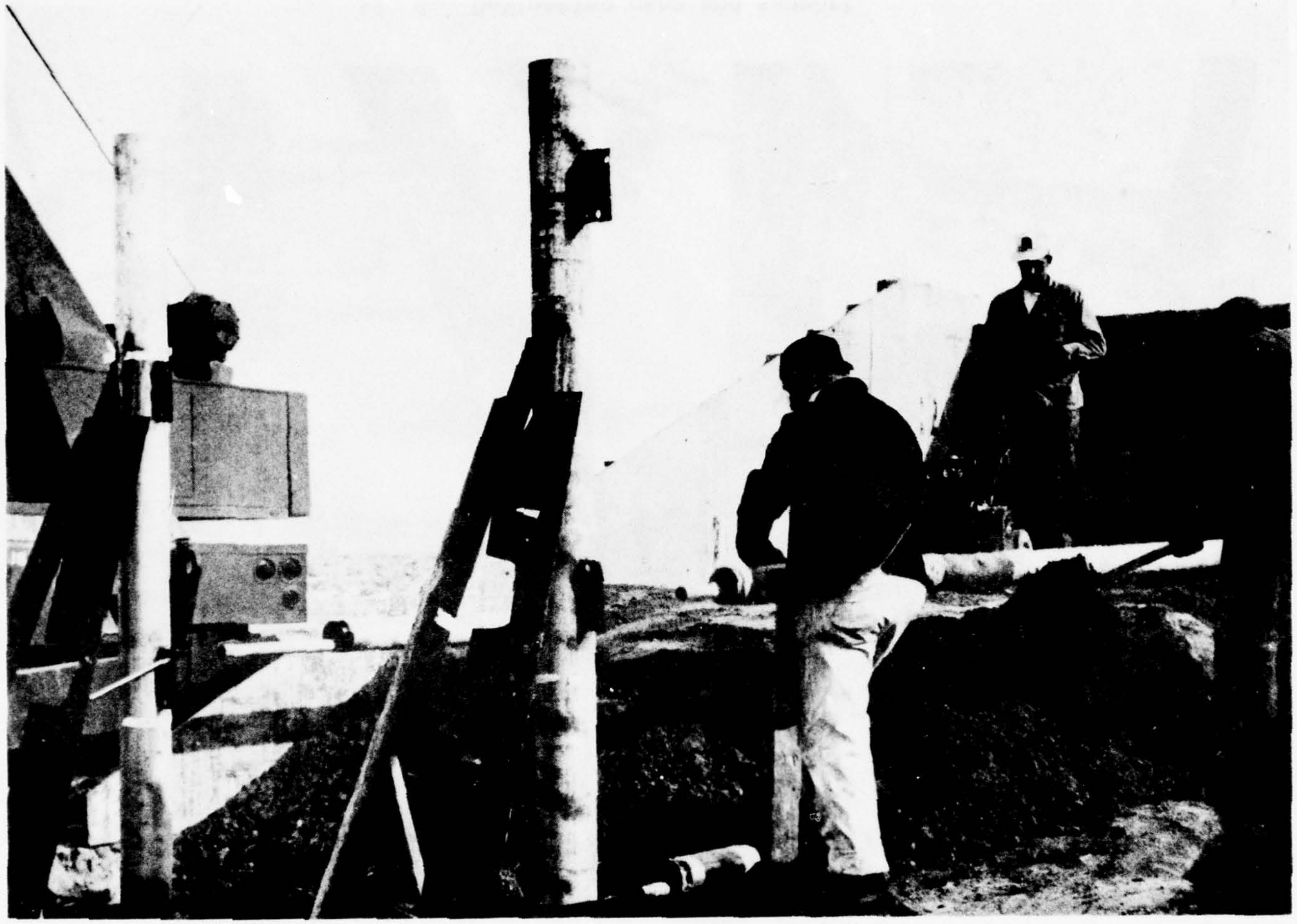


Fig 7 Gage mount construction

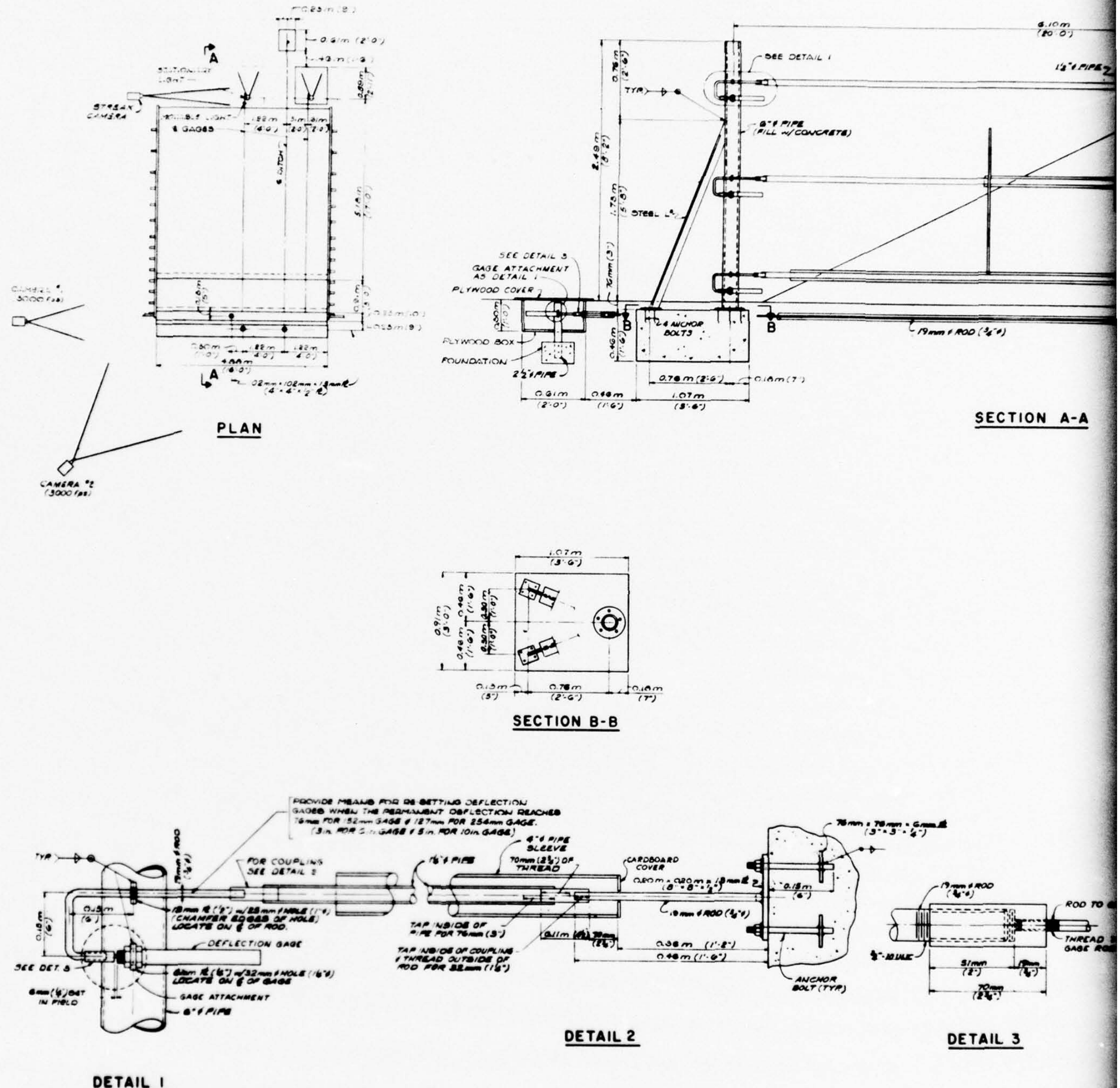
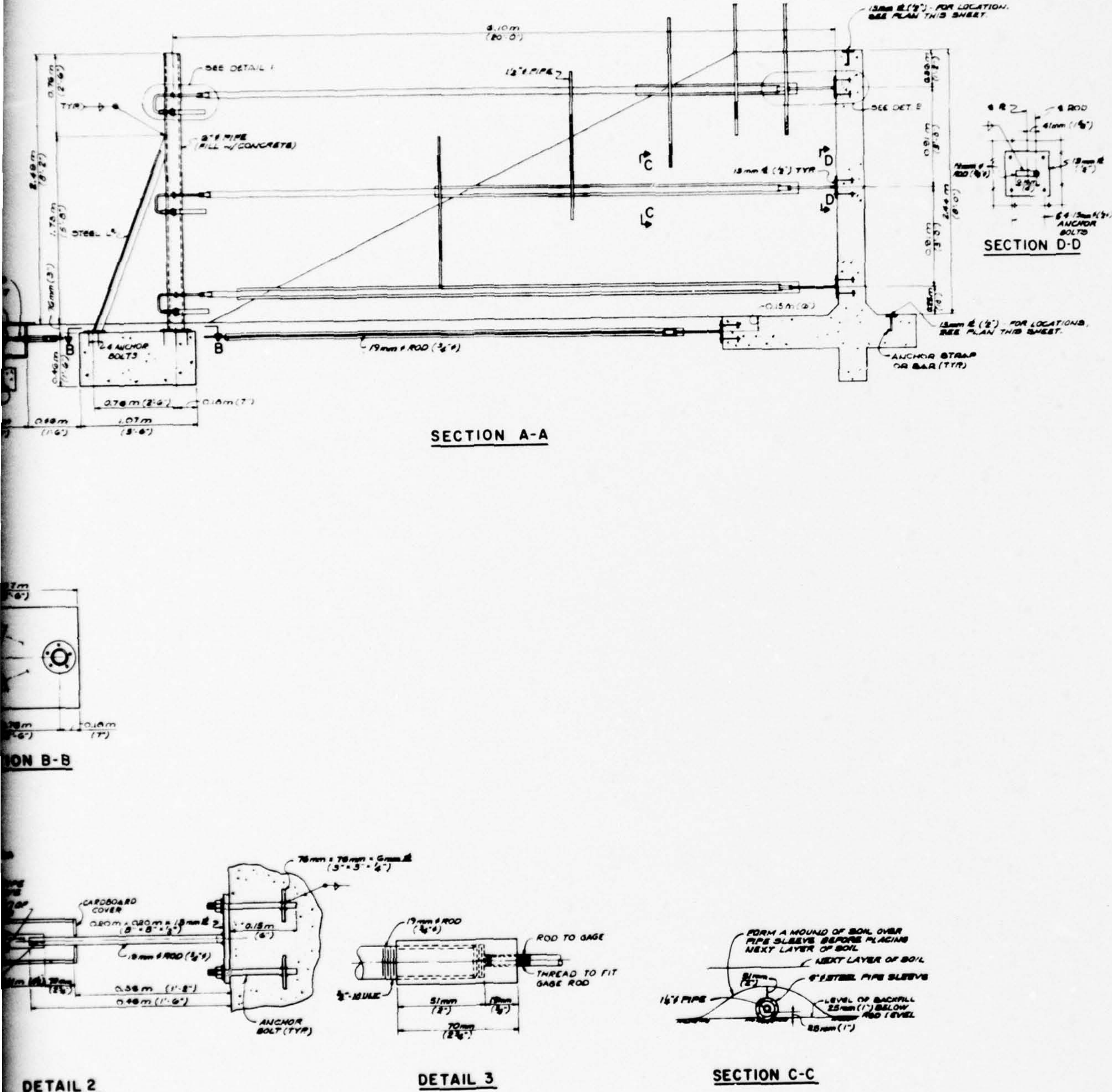


Fig 8 Deflection gage and support details



Deflection gage and support details

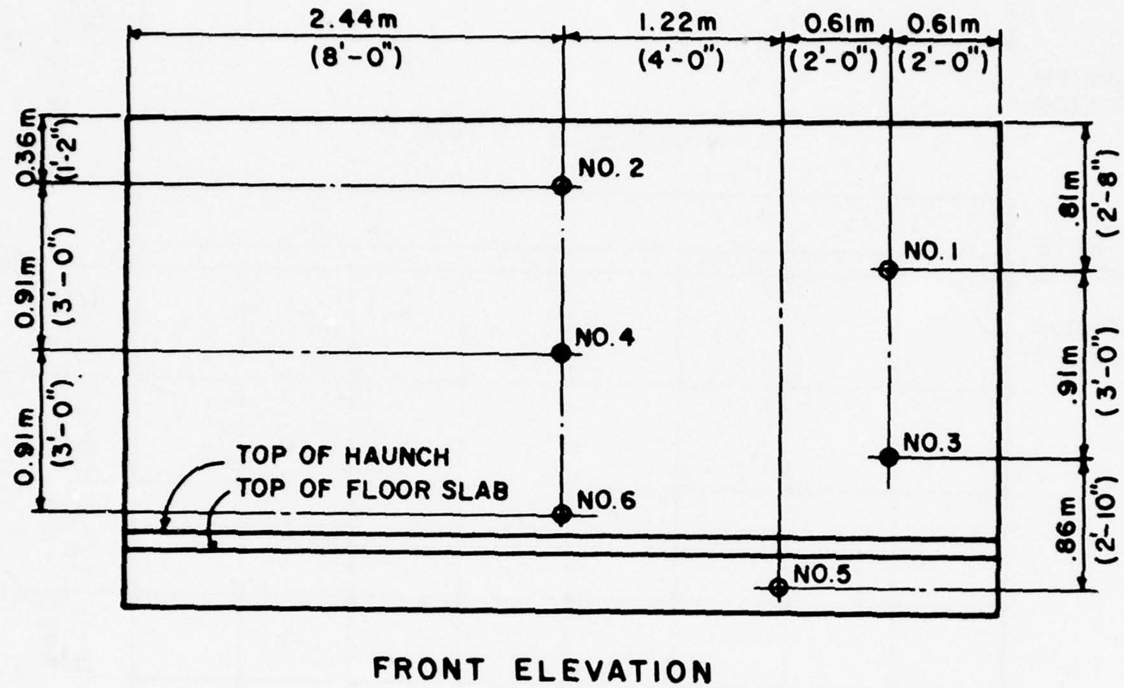


Fig 9 Deflection gage attachment locations

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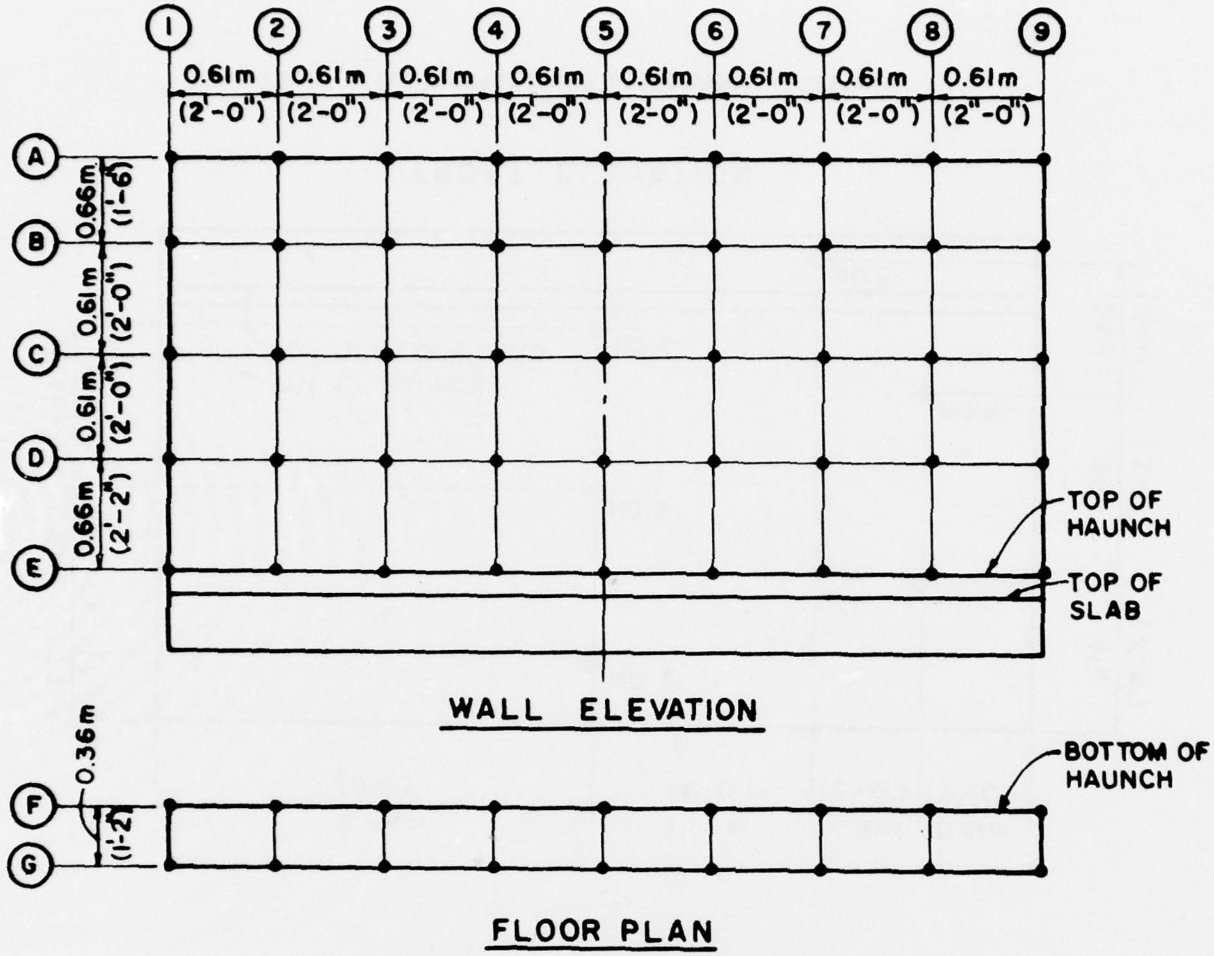

Fig 10 Location of hand measurements

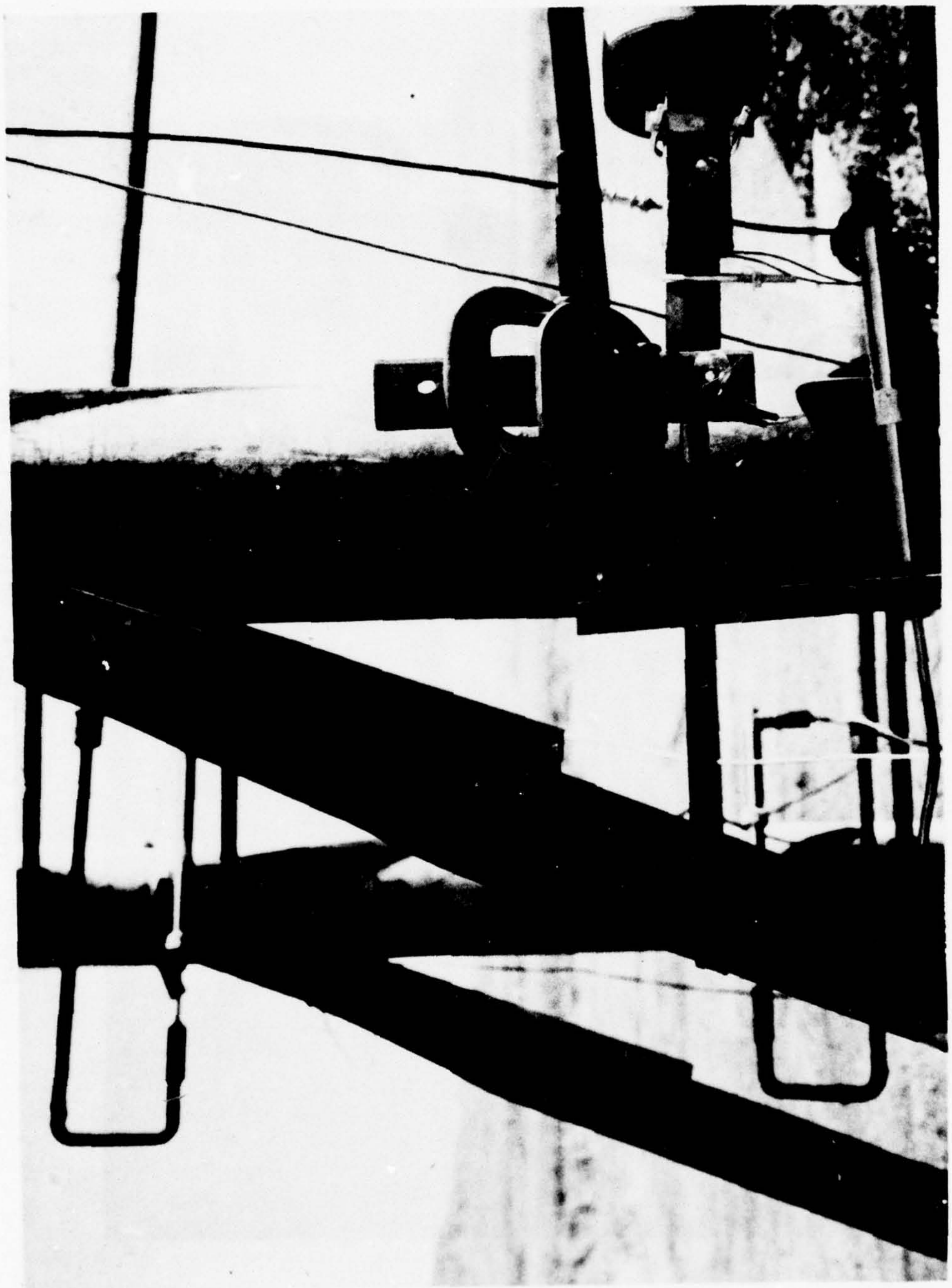

Fig 11 Streak gage lights

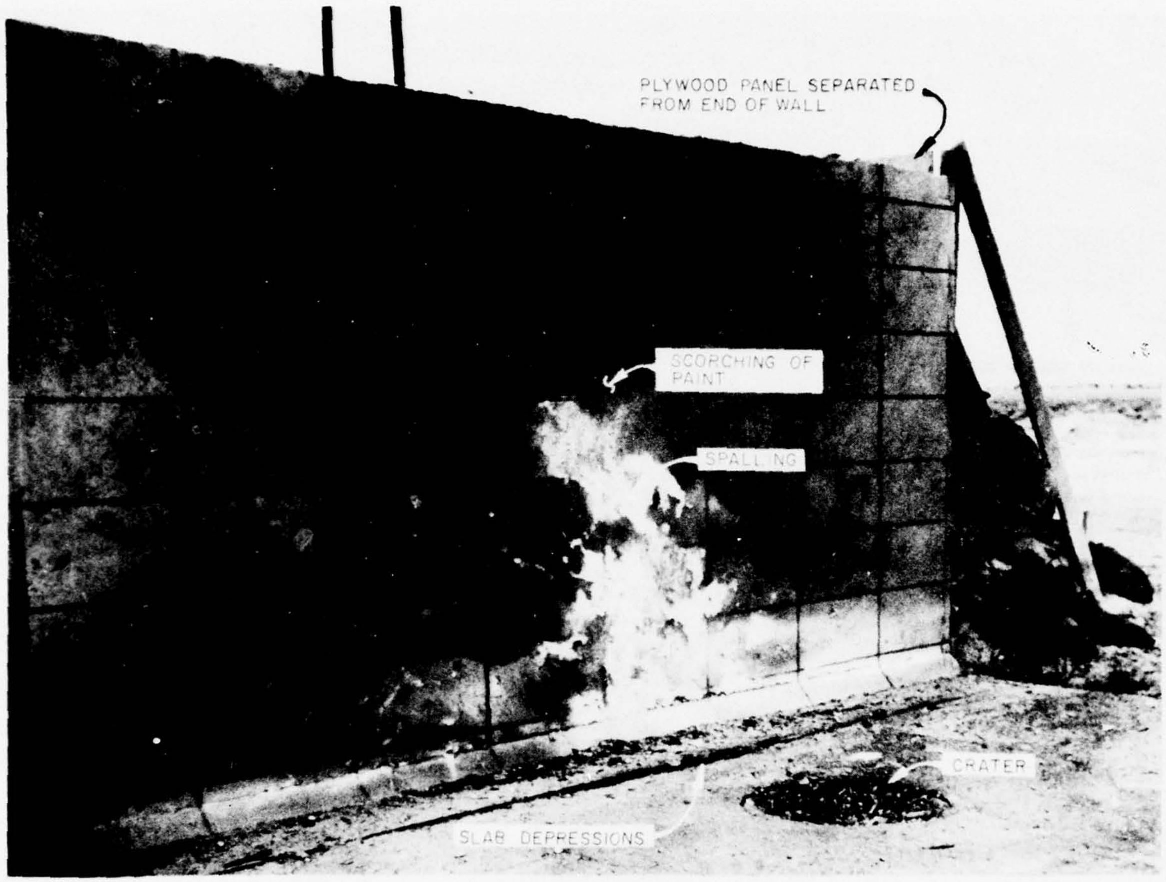

Fig 12 Front face damage, Wall No. 1, Test No. 1

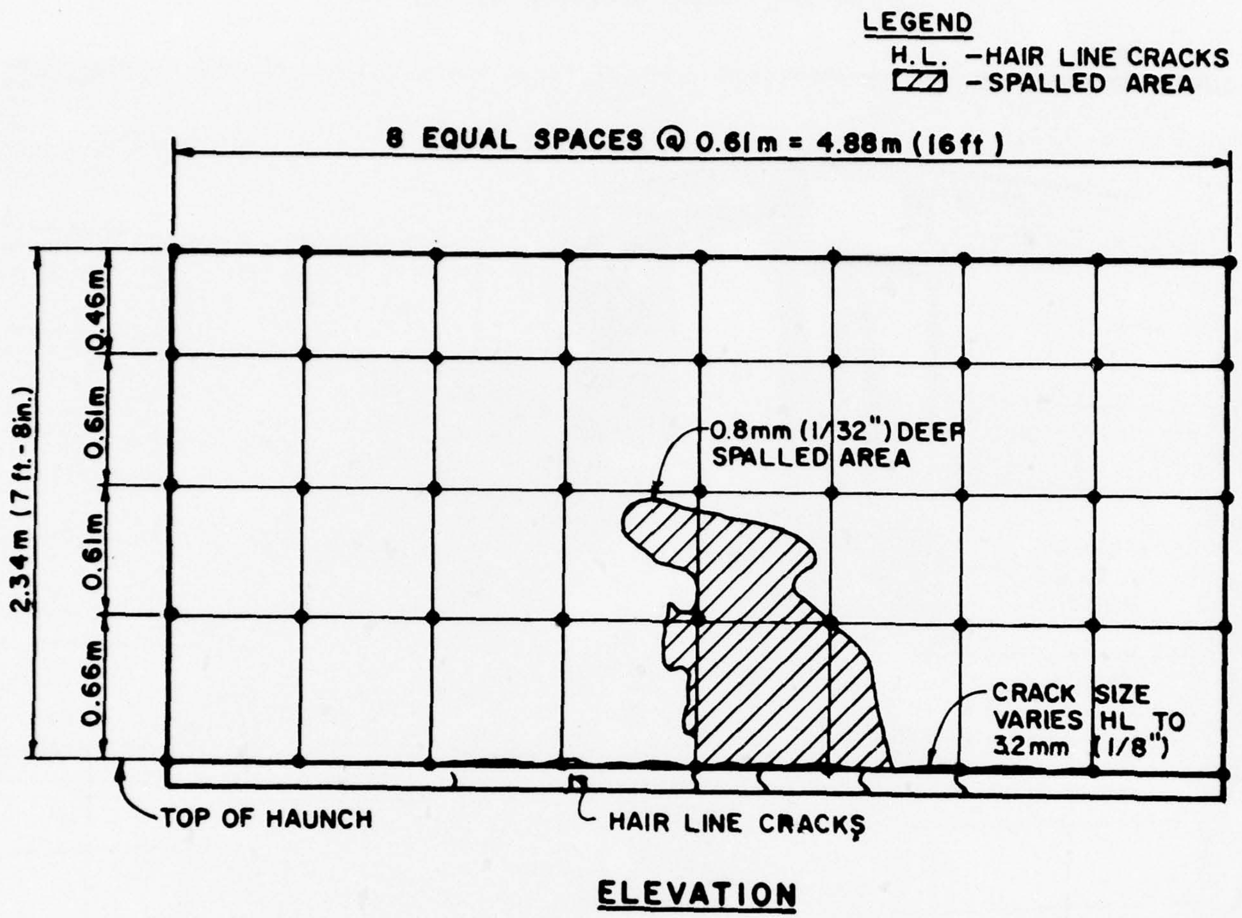

Fig 13 Crack patterns, Wall No. 1, Test No. 1

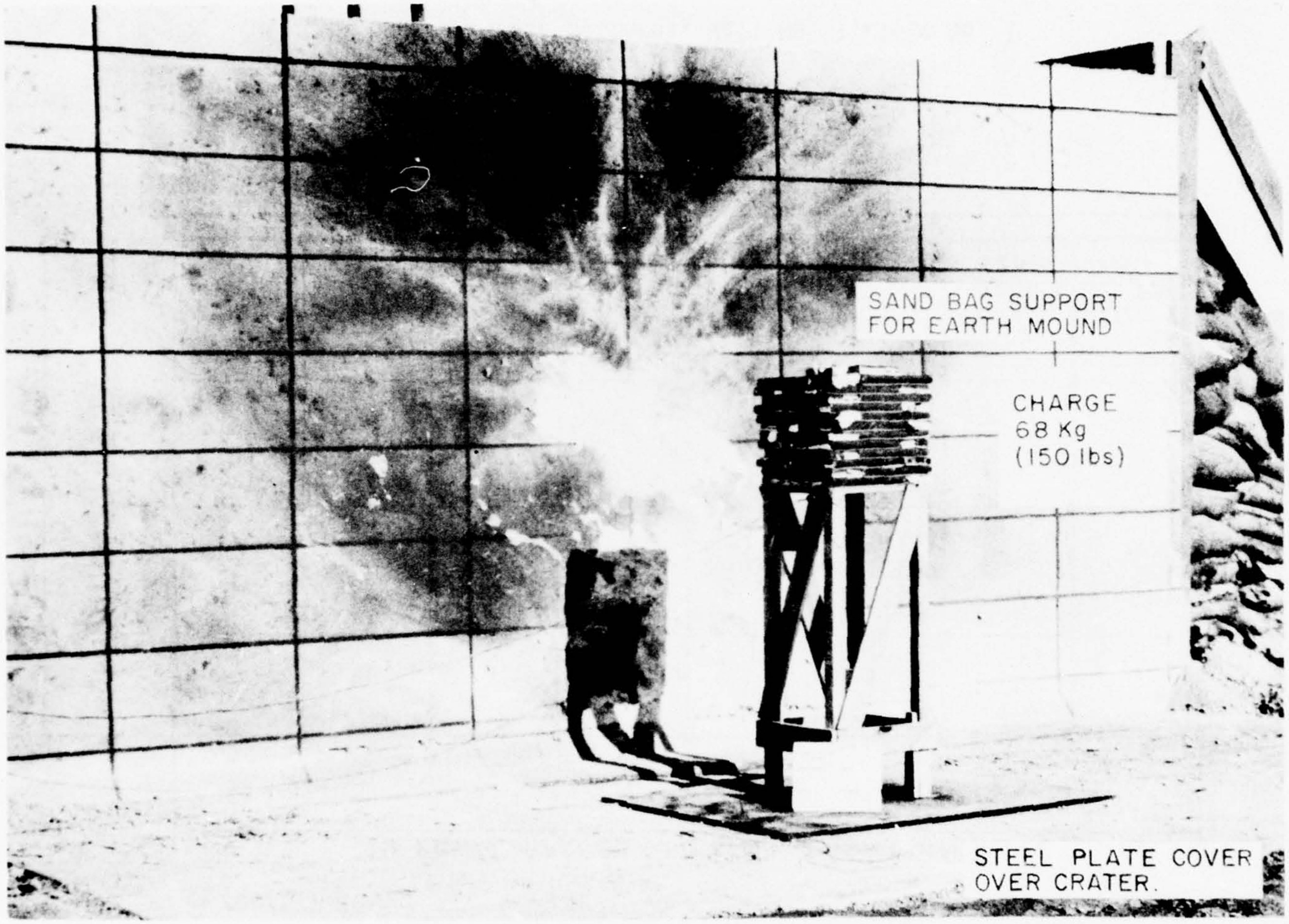

Fig 14 Pre-test setup, Test No. 2

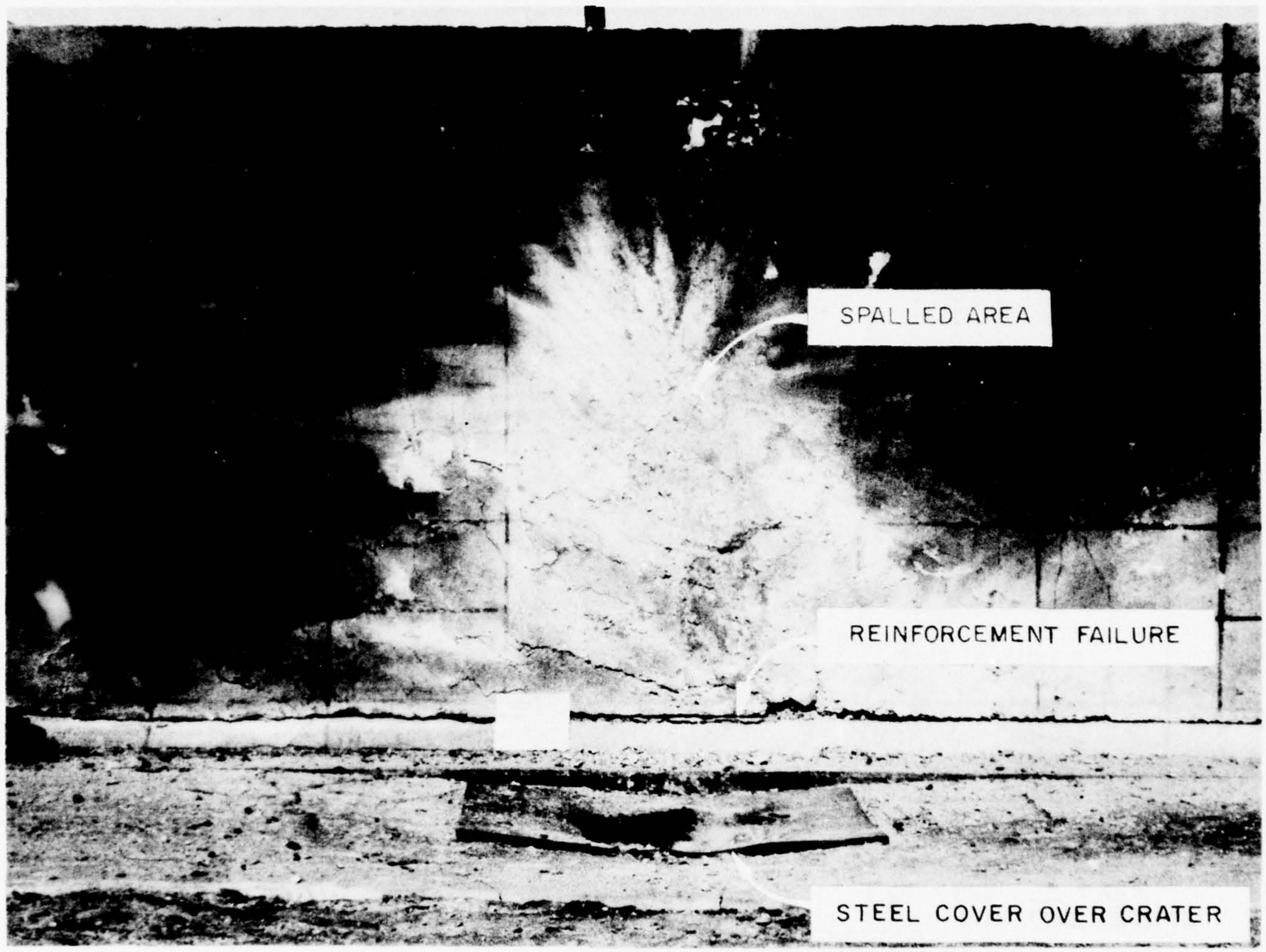

Fig 15 Front face damage, Wall No. 1, Test No. 2

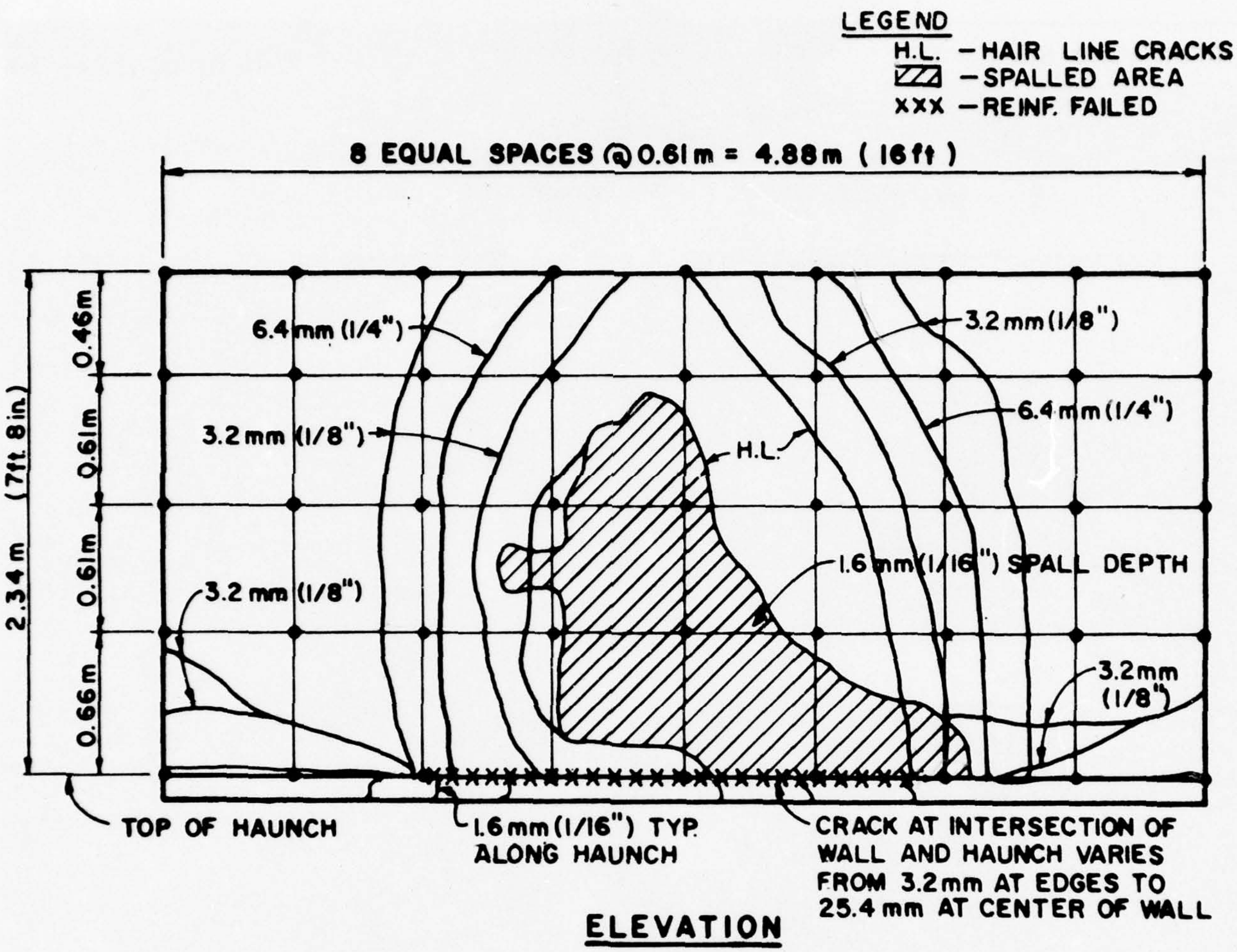

Fig 16 Crack patterns, Wall No. 1, Test No. 2

Fig 17 Sandbag and mount support damage, Test No. 2

Fig 18 Pre-test setup, Test No. 3

Fig 19 Front face damage, Wall No. 1, Test No. 3

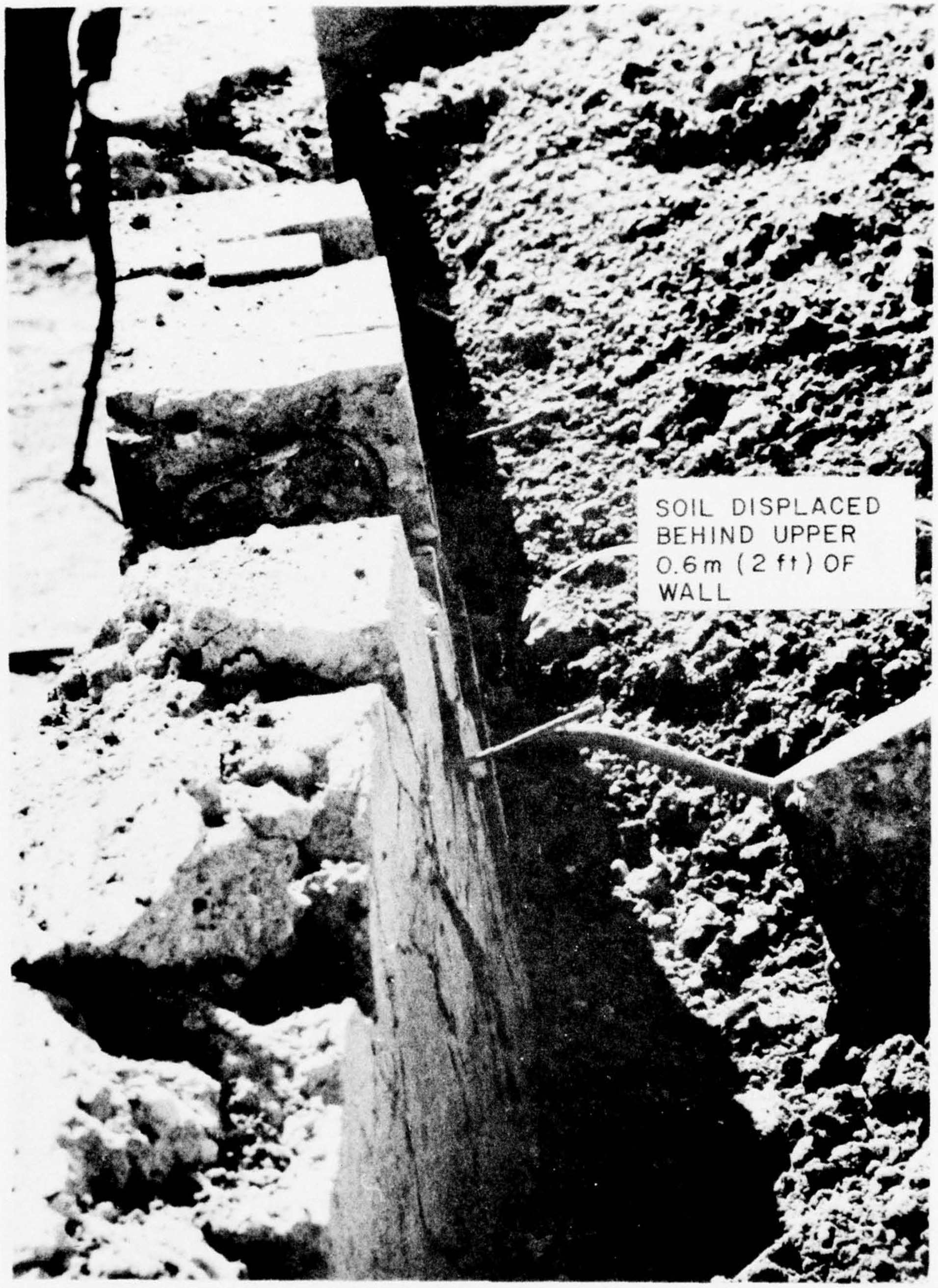

Fig 20 Soil displacement at rear of Wall No. 1, Test No. 3

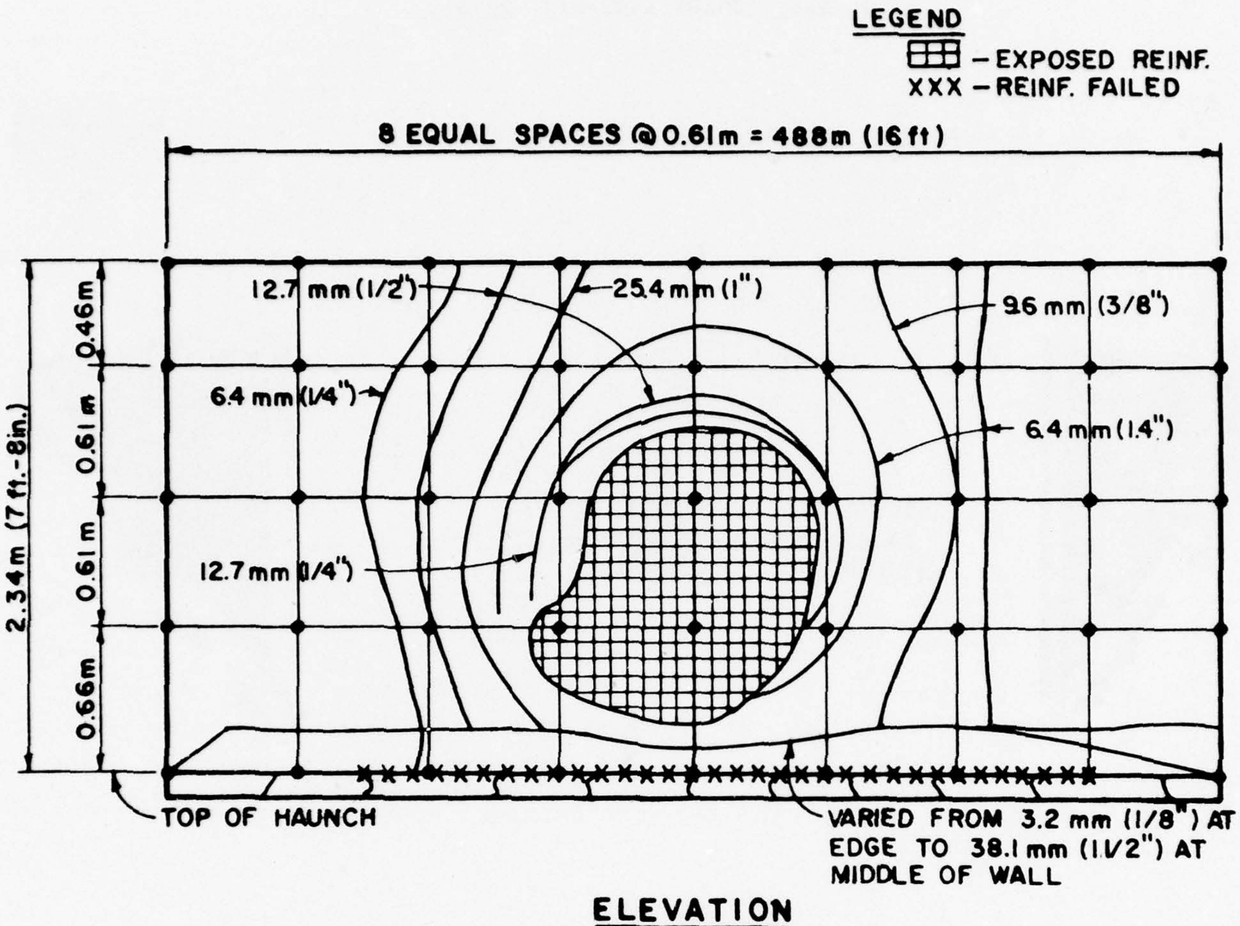

Fig 21 Crack patterns, Wall No. 1, Test No. 3

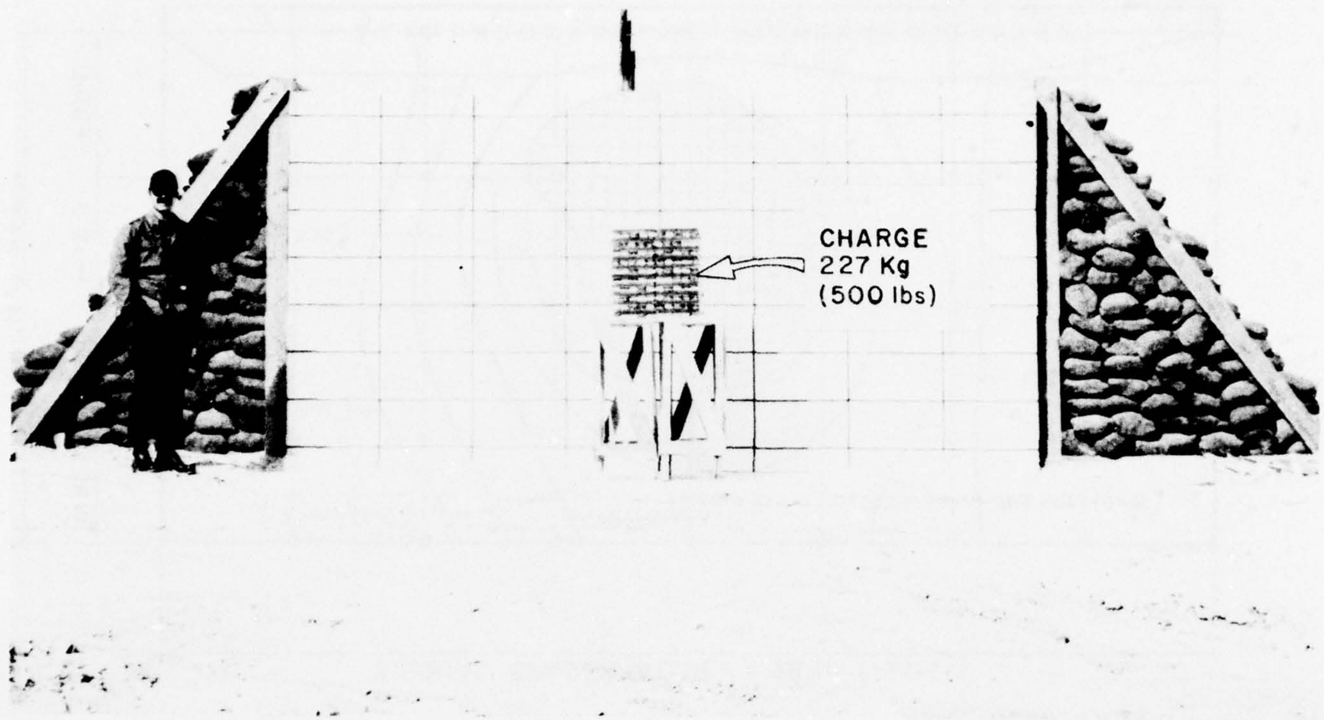

Fig 22 Pre-test setup, Test No. 4

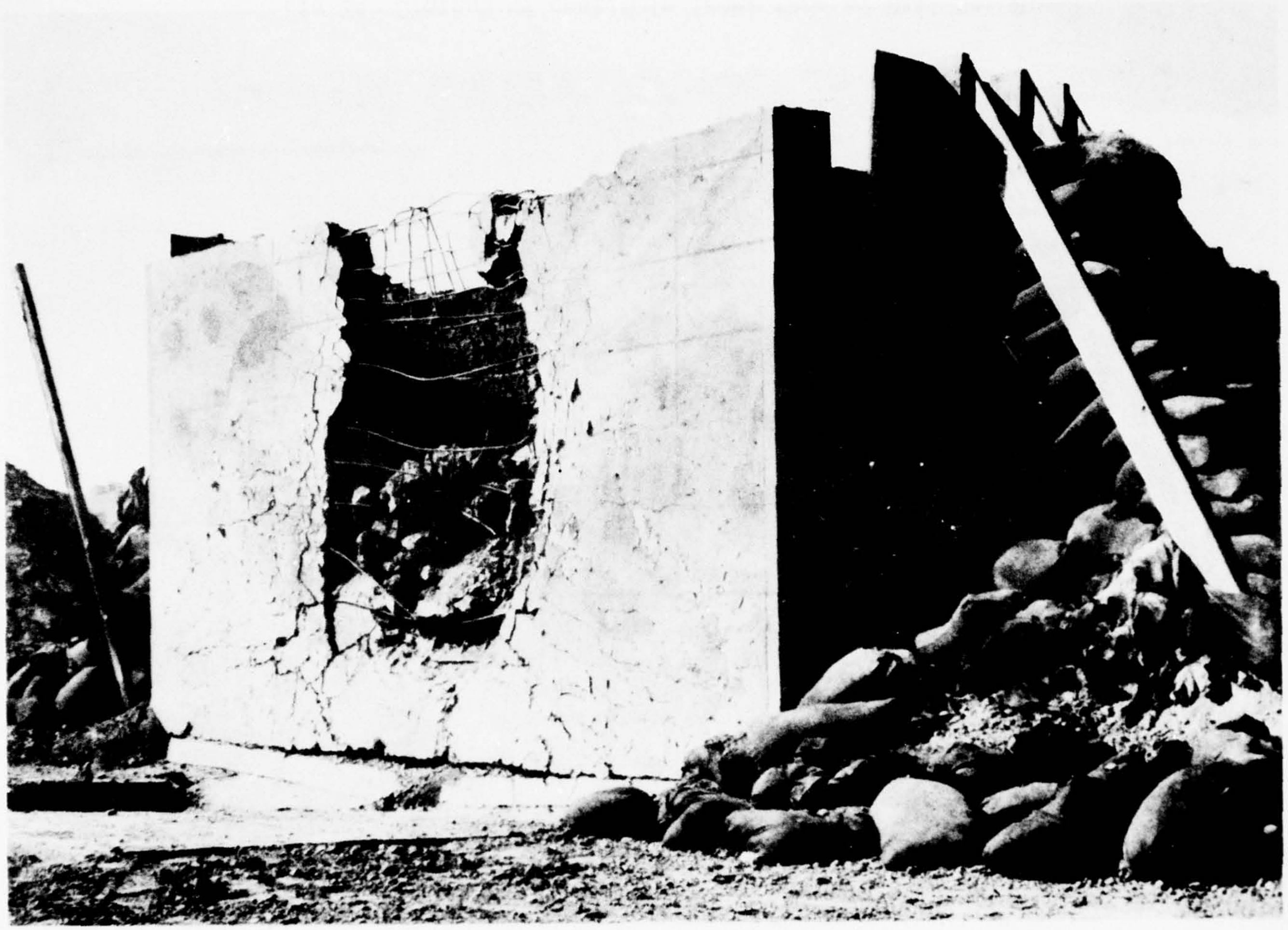

Fig 23 Front face damage, Wall No. 2, Test No. 4

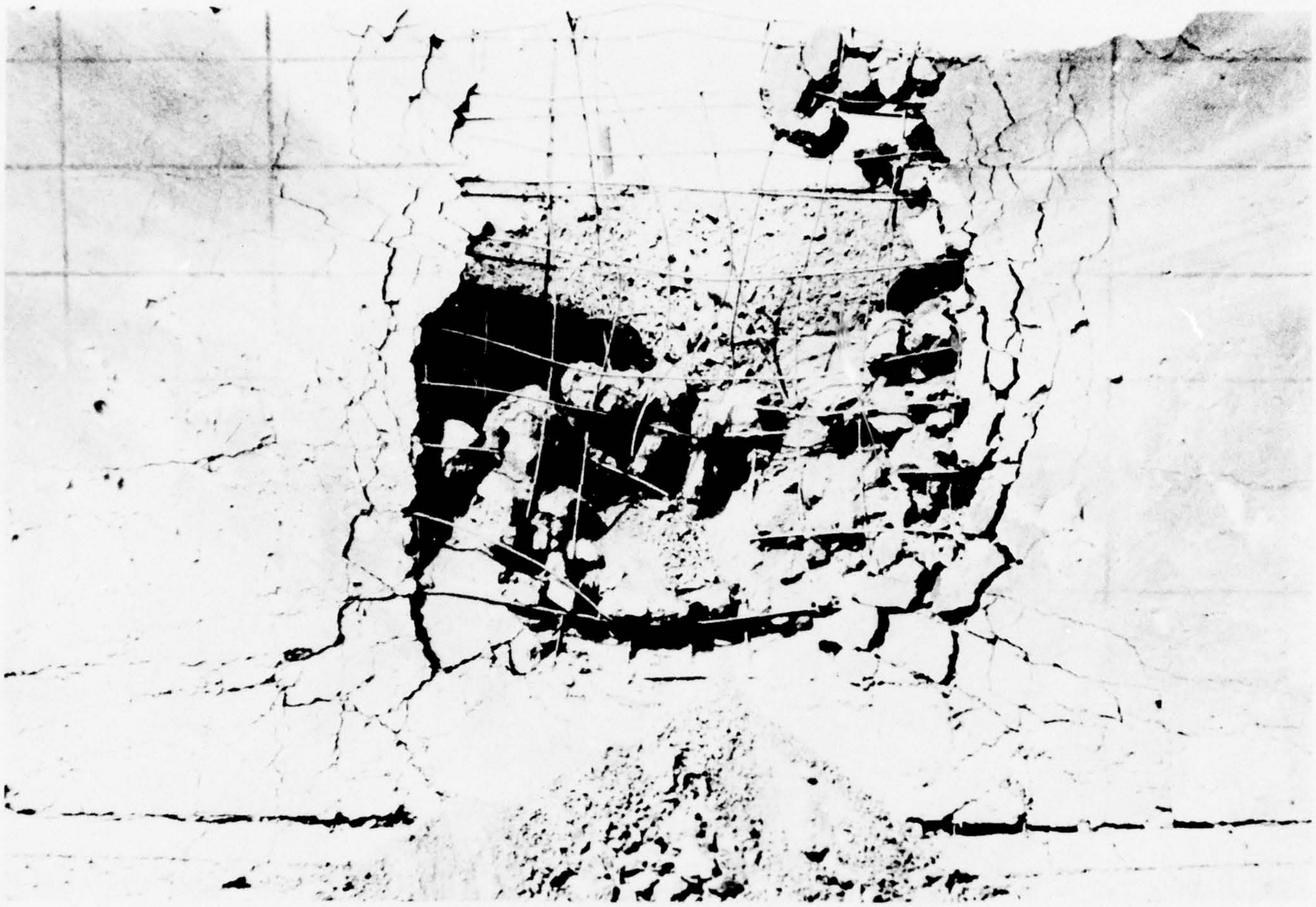

Fig 24 Closeup of crater in front face of Wall No. 2, Test No. 4

Fig 25 Debris from Wall No. 2, Test No. 4

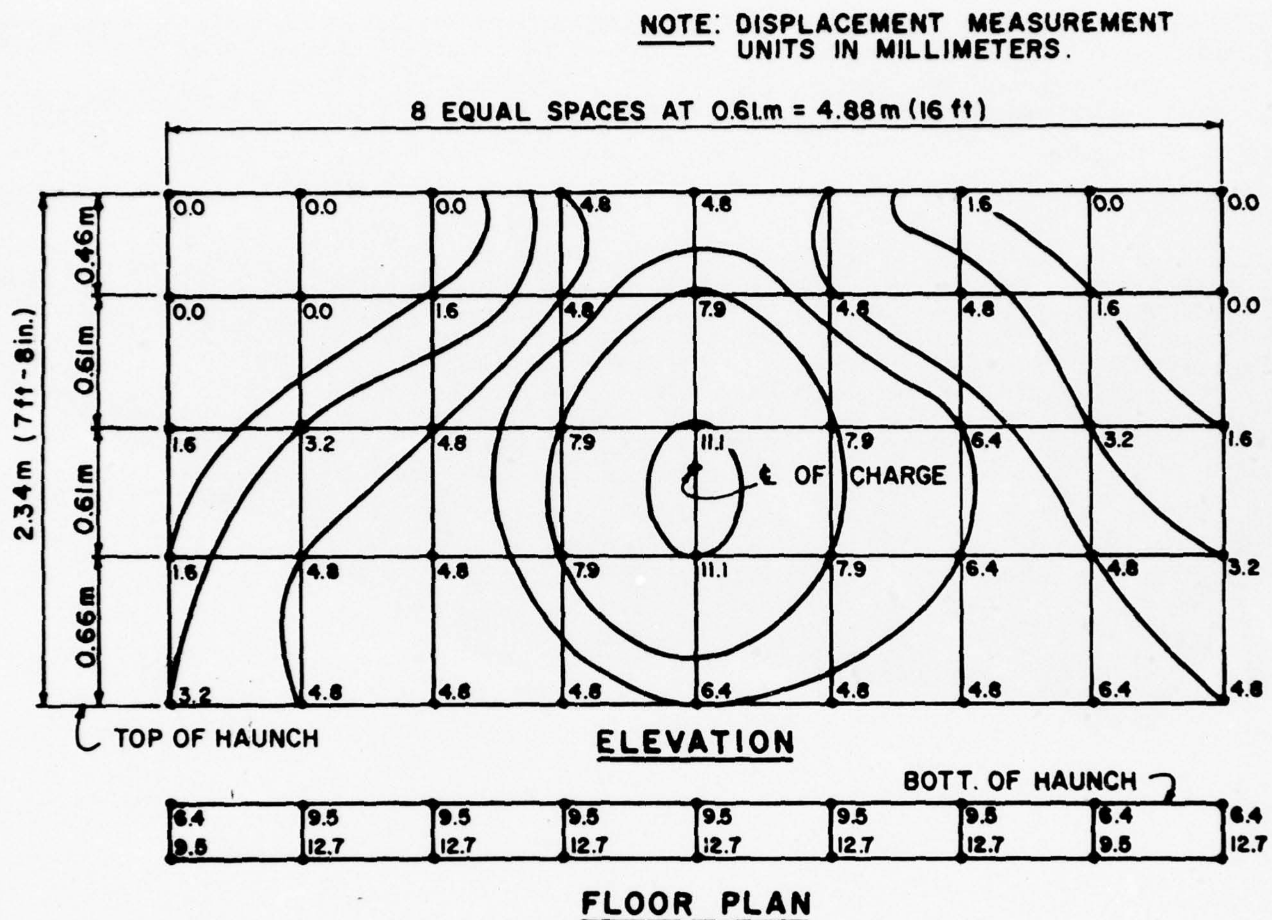

Fig 26 Permanent deflection patterns, Wall No. 1, Test No. 1

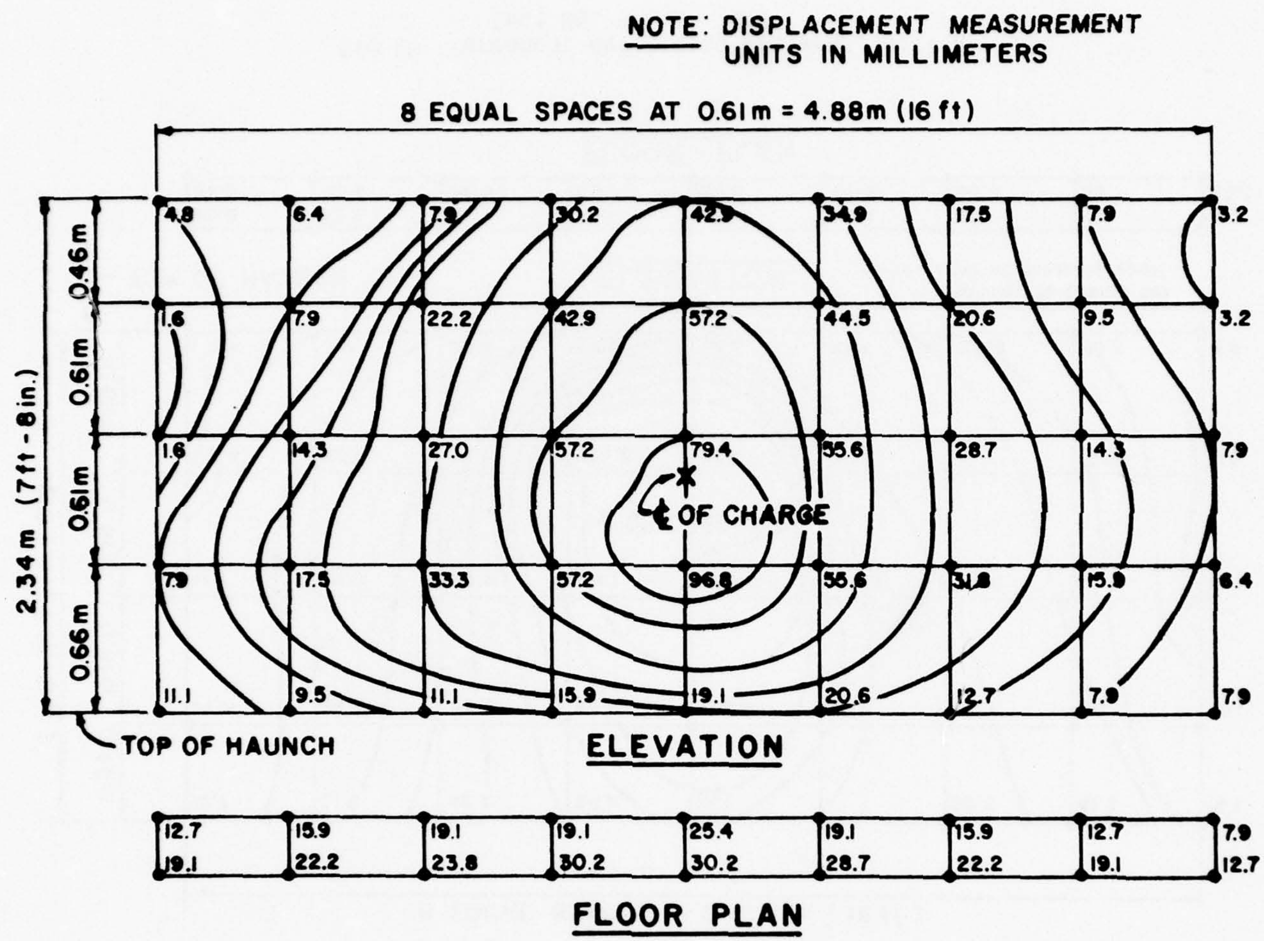

Fig 27 Permanent deflection patterns, Wall No. 1, Test No. 2

NOTES: 1. DISPLACEMENT MEASUREMENT UNITS IN MILLIMETERS.
2. EXCEPT AS NOTED ALL MEASUREMENTS INSIDE SPALLED AREA ARE TO REINFORCEMENT.

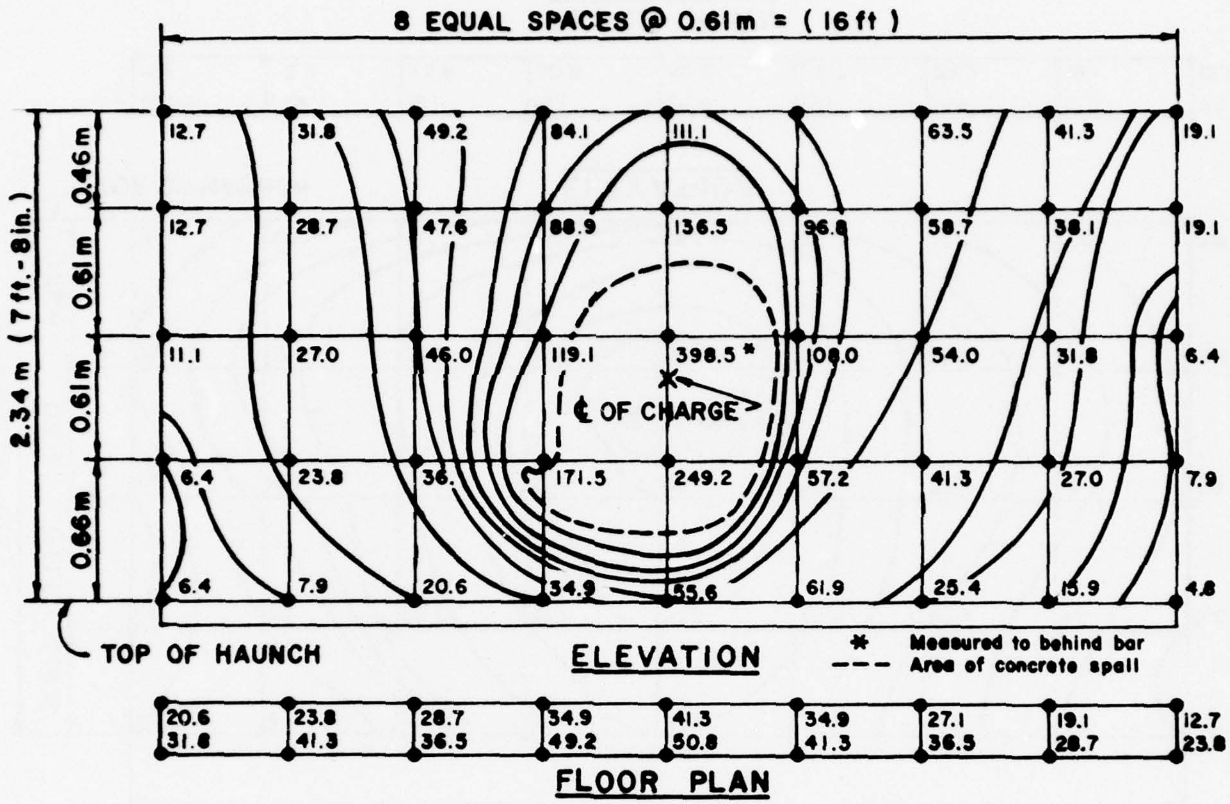

Fig 28 Permanent deflection patterns, Wall No. 1, Test No. 3

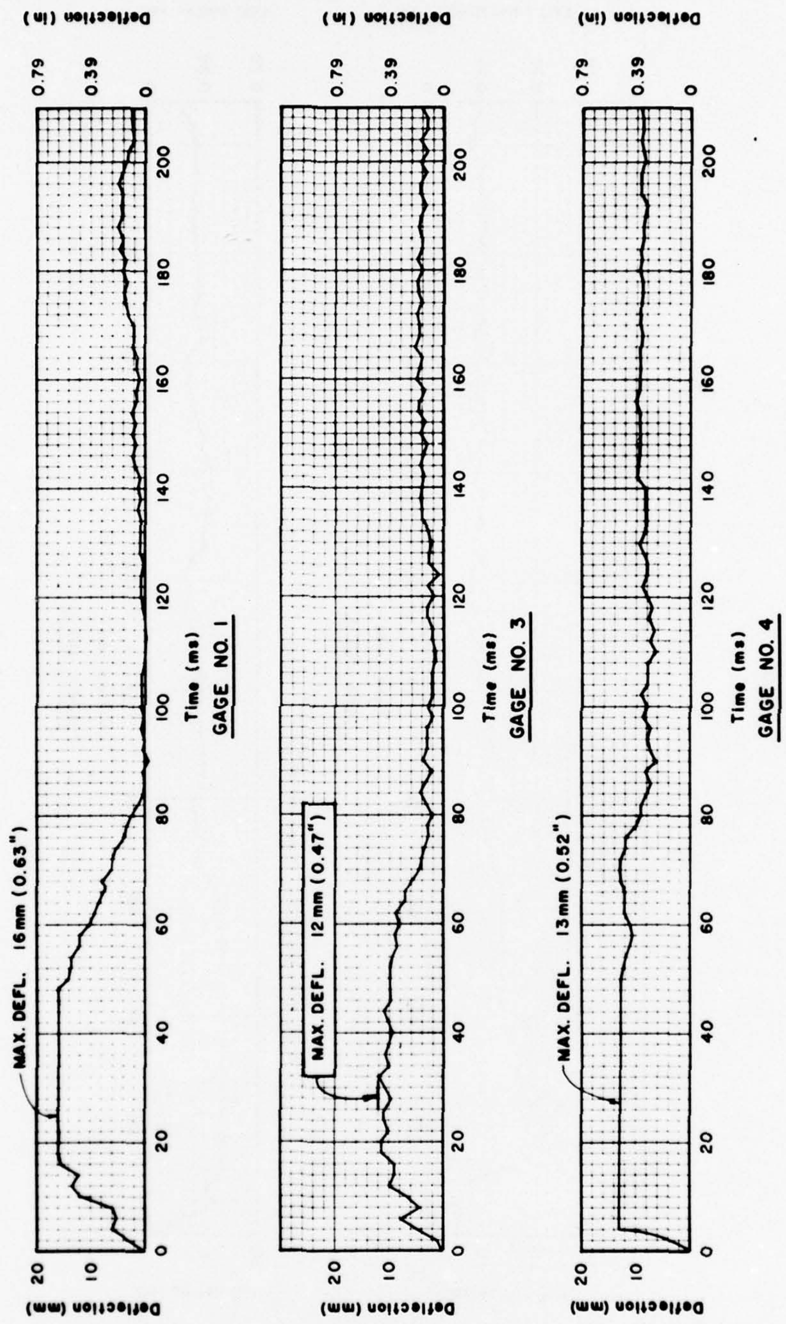

Fig 29 Deflection gage measurements, gages 1, 3 and 4, Test No. 1

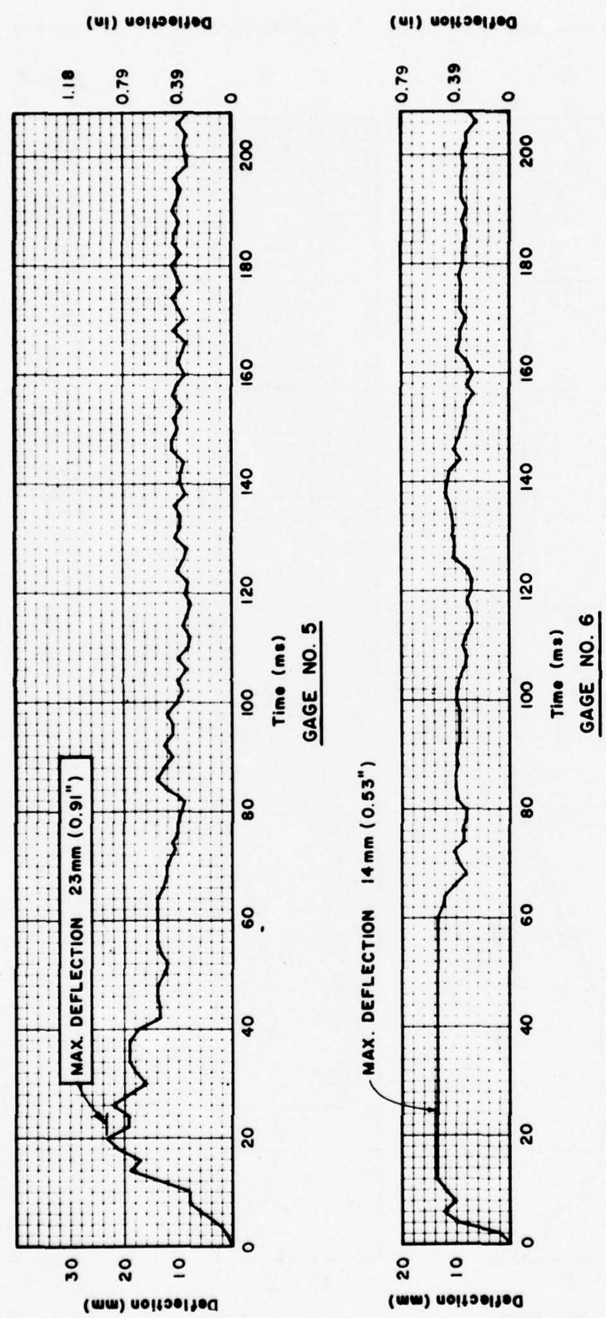

Fig 30 Deflection gage measurements, gages 5 and 6, Test No. 1

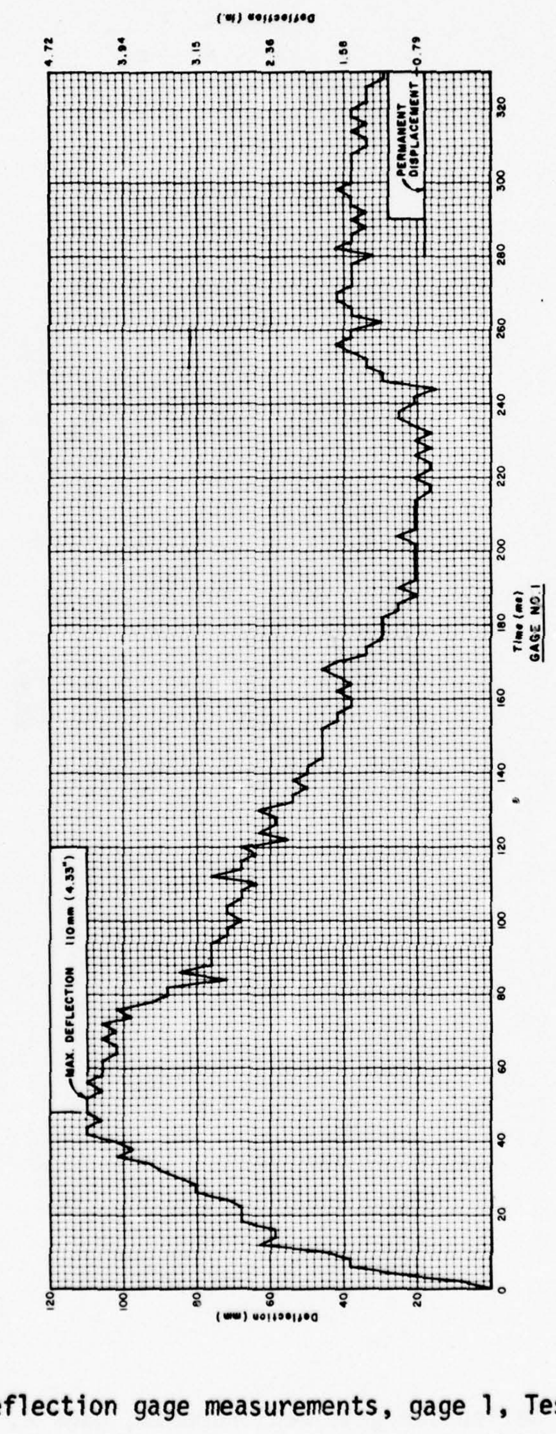

Fig 31 Deflection gage measurements, gage 1, Test No. 2

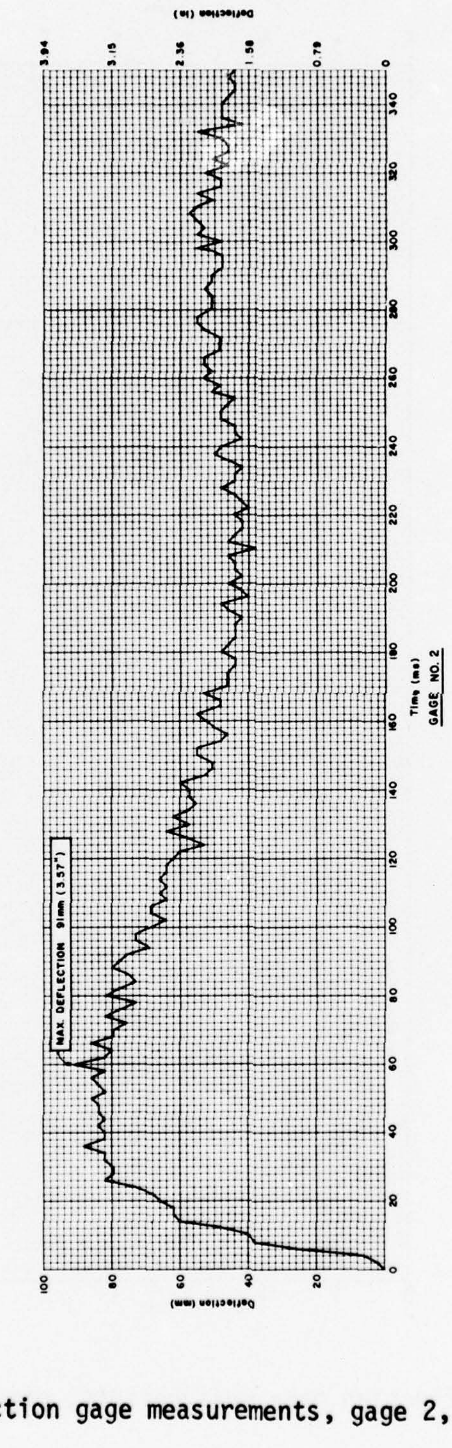

Fig 32 Deflection gage measurements, gage 2, Test No. 2

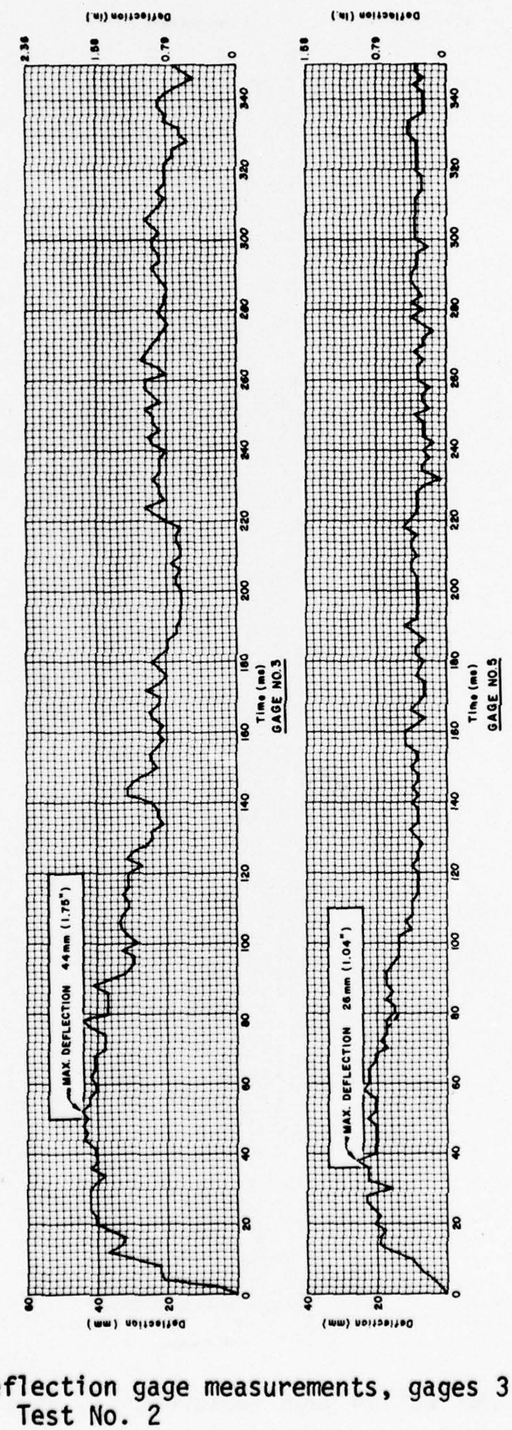

Fig 33 Deflection gage measurements, gages 3 and 5, Test No. 2

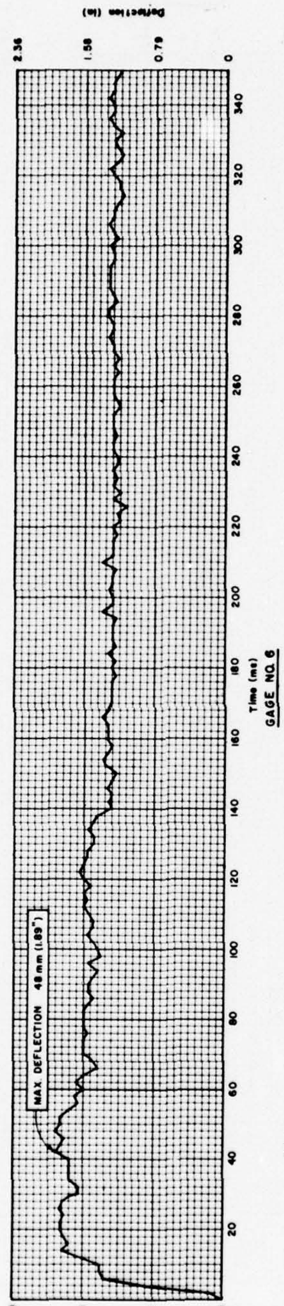

Fig 34 Deflection gage measurements, gage 6, Test No. 2

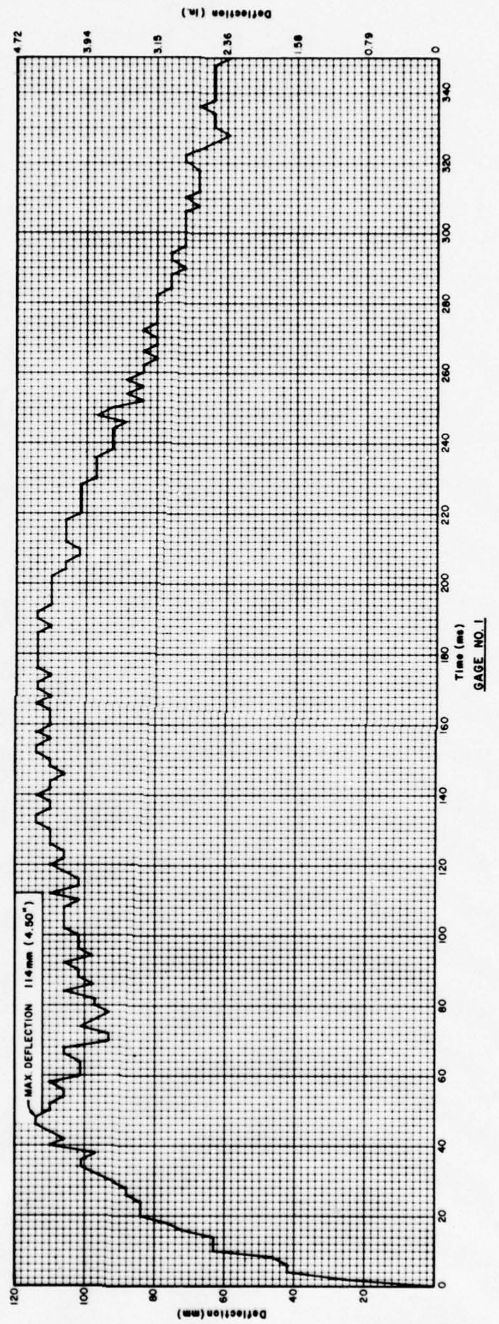

Fig 35 Deflection gage measurements, gage 1, Test No. 3

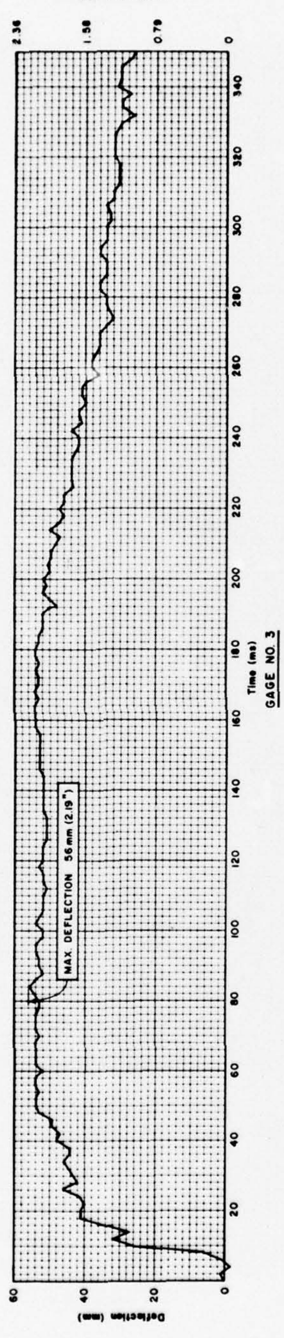

Fig 36 Deflection gage measurements, gage 3, Test No. 3

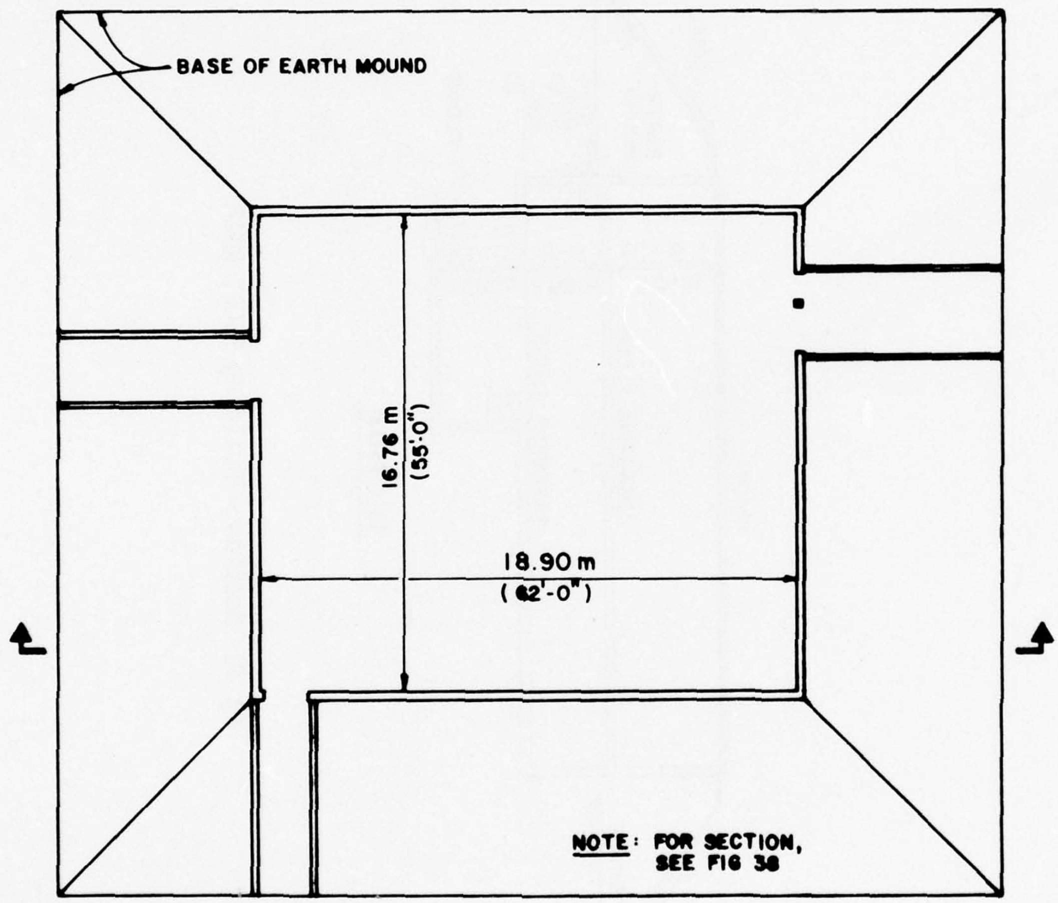

Fig 37 Floor plan - Building 9502, RAAP

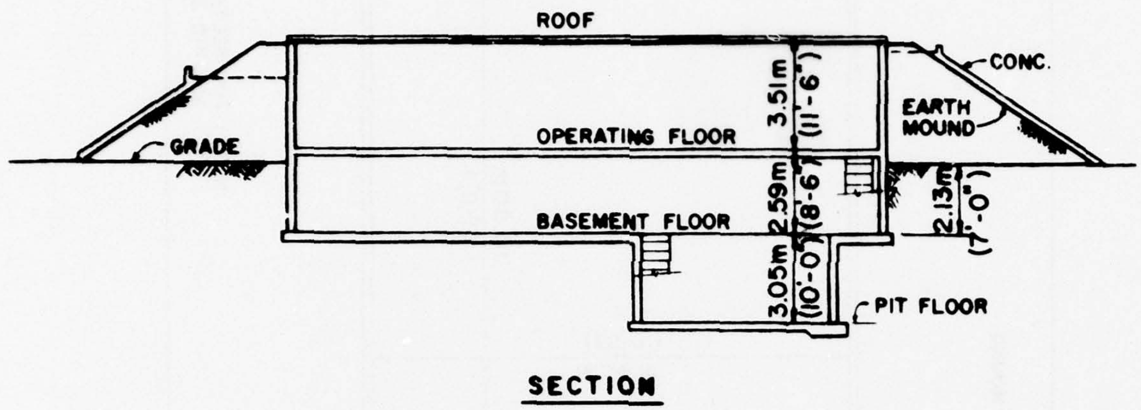

Fig 38 Section - Building 9502, RAAP

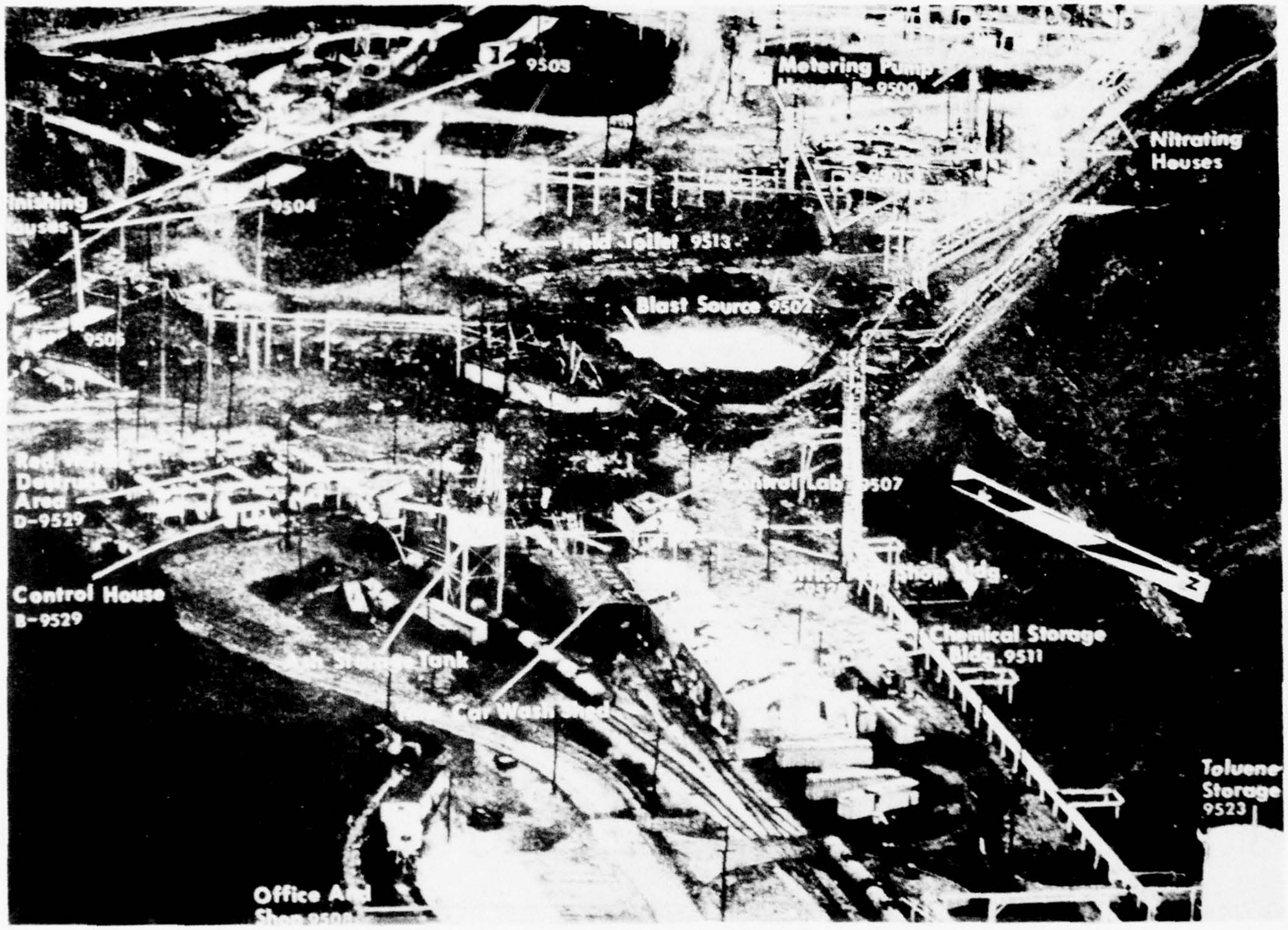

Fig 39 Post-explosion view of Building 9502, RAAP

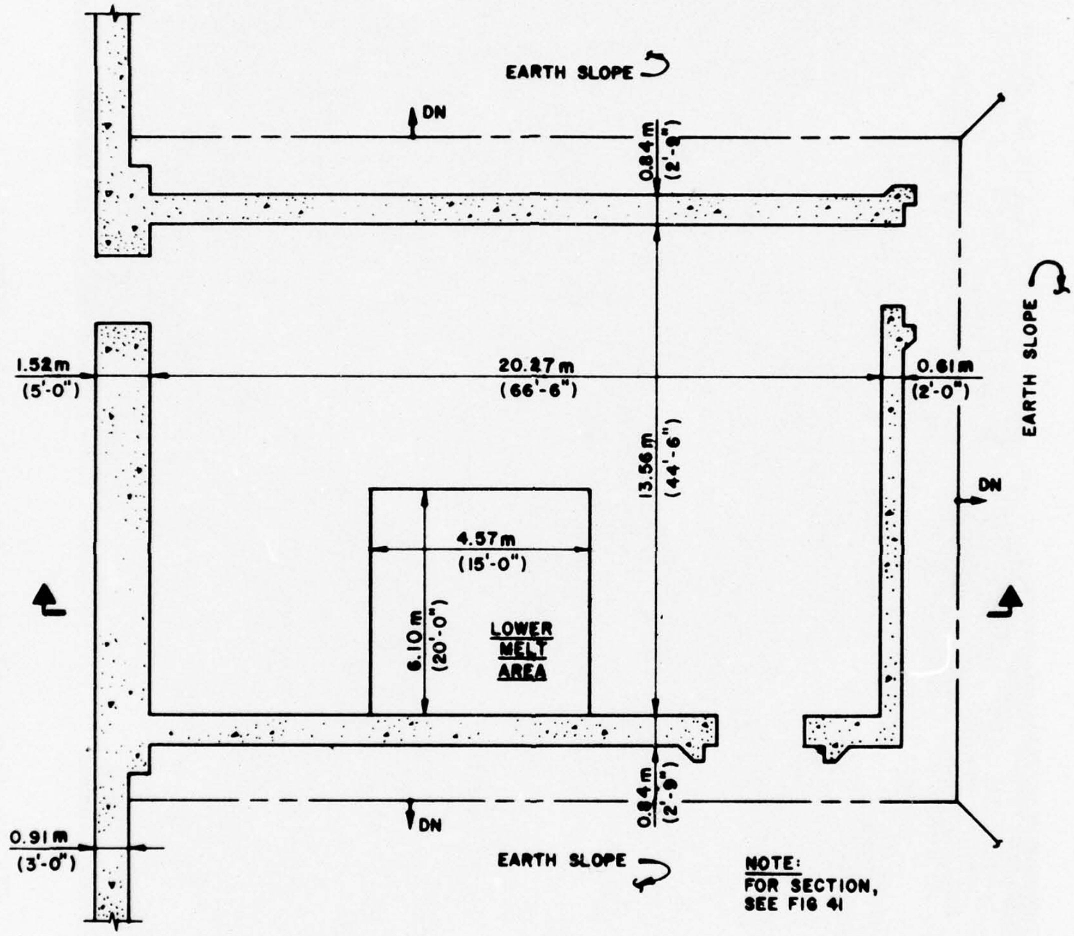

Fig 40 Floor plan - Melt/Pour Building, LSAAP

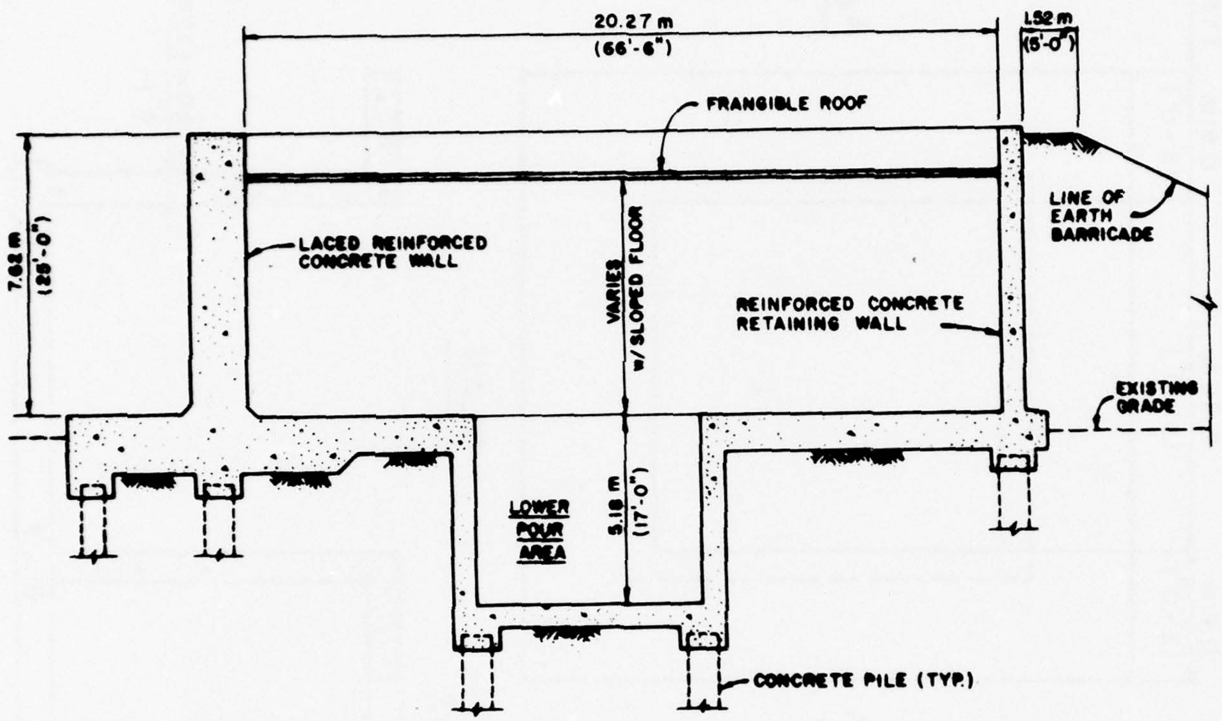

Fig 41 Section - Melt/Pour Building, LSAAP

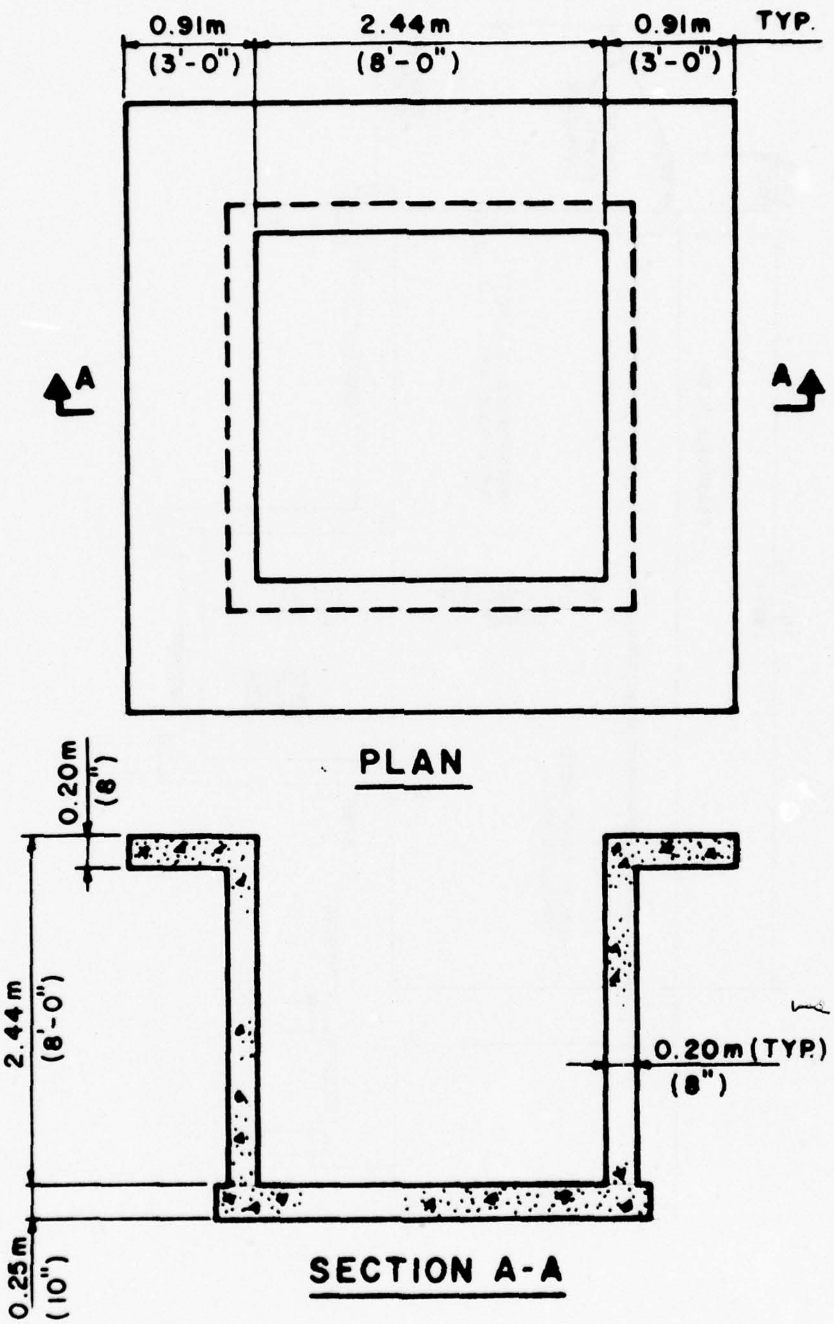

Fig 42 Test Cell No. 2 - Belowground Structure Tests

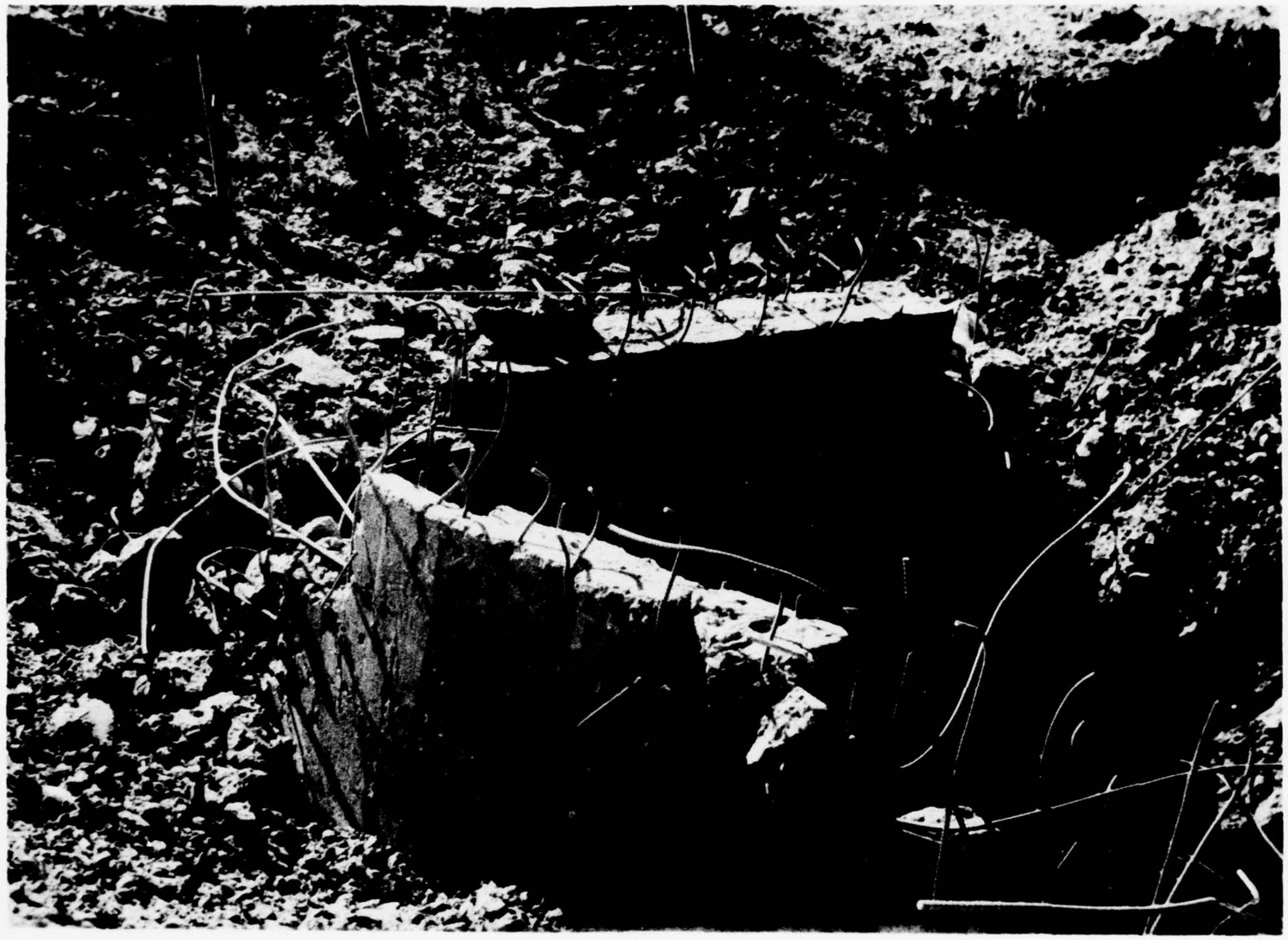

Fig 43 Test Results - Cell No. 2 - Belowground Structure Tests

APPENDIX

INTERNATIONAL SYSTEM OF UNITS

APPENDIX

INTERNATIONAL SYSTEM OF UNITS

General

This appendix deals with the conversion of quantities from the U. S. System of measurement to the International System of Units which is officially abbreviated as SI in all languages. It includes units most frequently used in the various fields of science and industry and conforms to the Metric Practice Guide as presented in the American Society for Testing and Materials Standard E 380.

SI Units and Prefixes

SI consists of seven base units, two supplementary units, a series of derived units consistent with the base and supplementary units, and a series of approved prefixes for the formation of multiples and sub-multiples of various units. A summary of the base units, supplementary units, derived units and prefixes is given below:

Base Units

Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

Supplementary Units

Quantity	Unit	Symbol
Plane angle	radian	rad
Solid angle	steradian	sr

Derived Units

Quantity	Unit	Symbol or Formula
Acceleration	meter per second squared	m/s^2
Activity (radioactive source)	disintegration per second	(disintegration)/s
Angular acceleration	radian per second squared	rad/s^2
Angular velocity	radian per second	rad/s
Area	square meter	m^2
Density	kilogram per cubic meter	kg/m^3
Electric capacitance	farad	F or A.s/V
Electrical conductance	siemens	S or A/V
Electric field strength	volt per meter	V/m
Electric inductance	henry	H or V.s/A
Electric potential difference	volt	V or W/A
Electric resistance	ohm	Ω or V/A
Electromotive force	volt	V or W/A
Energy	joule	J or N.m
Entropy	joule per kelvin	J/K
Force	newton	N or $kg.m/s^2$
Frequency	hertz	Hz or (cycle)/s
Illuminance	lux	lx or lm/m^2
Luminance	candela per square meter	cd/m^2
Luminous flux	lumen	lm or cd.sr
Magnetic field strength	ampere per meter	A/m
Magnetic flux	weber	Wb or V.s
Magnetic flux density	tesla	T or Wb/m^2
Magnetomotive force	ampere	A
Power	watt	W or J/s
Pressure	pascal	Pa or N/m^2
Quantity of electricity	coulomb	C or A.s
Quantity of heat	joule	J or N.m
Radiant intensity	watt per steradian	W/s.r
Specific heat	joule per kilogram-kelvin	J/kg.K
Stress	pascal	Pa or N/m^2
Thermal conductivity	watt per meter-kelvin	W/m.K
Velocity	meter per second	m/s
Viscosity, dynamic	pascal-second	Pa.s
Viscosity, kinematic	square meter per second	m^2/s
Voltage	volt	V or W/A

Derived Units (continued)

Quantity	Unit	Symbol or Formula
Volume	cubic meter	m^3
Wavenumber	reciprocal meter	(wave)/m
Work	joule	J or N.m

Prefixes

Multiplication	Prefix	Symbol
1,000,000,000,000 = 10^{12}	tera	T
1,000,000,000 = 10^{9}	giga	G
1,000,000 = 10^{6}	mega	M
1,000 = 10^{3}	kilo	k
100 = 10^{2}	hecto*	h
10 = 10^{1}	deka*	da
0.1 = 10^{-1}	deci*	d
0.01 = 10^{-2}	centi*	c
0.001 = 10^{-3}	milli	m
0.000,001 = 10^{-6}	micro	µ
0.000,000,001 = 10^{-9}	nano	n
0.000,000,000,001 = 10^{-12}	pico	p
0.000,000,000,000,001 = 10^{-15}	femto	f
0.000,000,000,000,000,001 = 10^{-18}	atto	a

*To be avoided where possible

Selection of prefixes representing steps of 1,000 is recommended for most multiple and submultiple prefixes. An exception is made in the case of area and volume used alone. When expressing a quantity by a numerical value and a unit, prefixes should preferably be chosen so that the numerical value lies between 0.1 and 1,000, except where certain multiples or submultiples have been agreed to for particular use. The same unit, multiple or submultiple is used for tabular values even though the series exceeds the preferred range 0.1 to 1,000. Double prefixes should not be used. Prefixes should not be used in the denominator of compound units, except for the kilogram which is a base unit of SI. However, prefixes may be applied to numerator of a combined unit. With SI units of higher order such as m^2, m^3, etc., the prefix is also raised to the same order; e.g., mm^3 is $10^{-9}m^3$ and not $10^{-3}m^3$. In such cases, the use of cm^2, cm^3, dm^2, dm^3 and similar nonpreferred prefixes is acceptable.

Mass, Force and Weight

The principal departure of SI from the gravimetric form of metric engineering units is the separate and distinct units for mass and force. The kilogram is restricted to the unit of mass. The newton is the unit of force and should be used in place of kilogram-force. Likewise, the newton instead of kilogram-force should be used in combination units which include force; e.g., pressure or stress (N/m^2=Pa), energy (N.m=J), and power (N.m/s=W).

Considerable confusion exists in the use of the terms mass and weight. Mass is a property of matter to which it owes its inertia. If a body or particle of matter at rest on the earth's surface is released from the forces holding it at rest, it will experience the acceleration of free fall (or acceleration of gravity, g). The force required to restrain it against free fall is commonly called weight. This force is proportional to the mass of the body and is often expressed in mass units (kg), but as it is a force it should be expressed in force units (N). The acceleration of free fall (g) varies in time and space; weight (which is proportional to it) does too, although mass does not. Further confusion arises in the measuring of weight because of the buoyant effect of the medium in which the weighing is performed. In common parlance the term weight is used where the technically correct word is mass and, therefore, the use of the term weight should be avoided in technical practice.

Conversion and Rounding Rules

Conversion of quantities should be handled with careful regard to the implied correspondence between the accuracy of the data and the given number of digits. In all conversions, the number of significant digits retained should be such that accuracy is neither sacrificed nor exaggerated. Proper conversion procedure is to multiply the specific quantity by the conversion factor exactly as given and then round to the appropriate number of significant digits.

The following table contains conversion factors that give exact or seven-figure accuracy where the nature of the dimension makes this degree of accuracy practical:

Selected Conversion Factors

To convert from	to	Multiply by
atmosphere (technical = 1 kfg/cm^2)	pascal (Pa)	9.806 650*x10^4
bar	pascal (Pa)	1.000 000*x10^5
board foot	meter^3(m^3)	2.359 737x10^{-3}
British thermal unit (International Table)	joule (J)	1.055 056x10^3
Btu (International Table) - in./s-ft^2-°F (k, thermal conductivity)	watt/meter-kelvin (W/m.K)	5.192 204x10^2
Btu (International Table) /hour	watt (W)	2.930 711x10^{-1}
calorie (International Table)	joule (J)	4.186 800*
centipoise	pascal-second (Pa.s)	1.000 000*x10^{-3}
centistokes	meter ^{2}/second (m^2/s)	1.000 000*x10^{-6}
degree (angle)	radian (rad)	1.745 329x10^{-2}
degree Fahrenheit	degree Celsius	t°c=(t°F-32)/1.8
fluid ounce (U.S.)	meter^3(m^3)	2.957 353x10^{-5}
foot	meter (m)	3.048 000*x10^{-1}
foot^2	meter^2(m^2)	9.290 304*x10^{-2}
foot^3 (volume and section modulus)	meter^3(m^3)	2.831 685x10^{-2}
foot/second	meter/second (m/s)	3.048 000*x10^{-1}
foot-pound-force	joule (J)	1.355 818
foot-pound-force/second	watt (W)	1.355 818
foot/second^2	meter/second^2 (m/s^2)	3.048 000*x10^{-1}
gallon (U.S.liquid)	meter^3(m^3)	3.785 412x10^{-3}
horsepower (electric)	watt (W)	7.460 000*x10^2
inch	meter (m)	2.540 000*x10^{-2}
inch^2	meter^2(m^2)	6.451 600*x10^{-4}
inch^3(volume and section modulus)	meter^3(m^3)	1.638 706x10^{-5}
inch of mercury (60°F)	pascal (Pa)	3.376 85x10^3
inch of water (60°F)	pascal (Pa)	2.488 4 x10^2
kilogram-force (kgf)	newton (N)	9.806 650*
kilogram-force/millimeter^2	pascal (Pa)	9.806 650*x10^6
kilogram-mass	kilogram (kg)	1.000 000*
kip (1000 lbf)	newton (N)	4.448 222x10^3
kip/inch^2(ksi)	pascal (Pa)	6.894 757x10^6
lux	lumen/meter^2(lm/m^2)	1.000 000*
minute (angle)	radian (rad)	2.908 882x10^{-4}
ounce-force (avoirdupois)	newton (N)	2.780 139x10^{-1}

*Exact

Selected Conversion Factors (Continued)

To convert from	to	Multiply by
ounce-mass (avoirdupois)	kilogram (kg)	$2.834\ 952 \times 10^{-2}$
ounce-mass/yard^2	kilogram/meter^2 (kg/m^2)	$3.390\ 575 \times 10^{-2}$
ounce (avoirdupois) (mass)/inch^3	kilogram/meter^3 (kg/m^3)	$1.729\ 994 \times 10^{3}$
ounce (U.S.fluid)	meter^3 (m^3)	$2.957\ 353 \times 10^{-5}$
pint (U.S.liquid)	meter^3 (m^3)	$4.731\ 765 \times 10^{-4}$
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound/force/inch^2(psi)	pascal (Pa)	$6.894\ 757 \times 10^{3}$
pound-mass (lbm avoirdupois)	kilogram (kg)	$4.535\ 924 \times 10^{-1}$
pound-mass-inch^2(moment of inertia)	kilogram-meter^2 (kg-m^2)	$2.926\ 397 \times 10^{-4}$
pound-mass/inch^3	kilogram/meter^3 (kg/m^3)	$2.767\ 990 \times 10^{4}$
quart (U.S.liquid)	meter^3 (m^3)	$9.463\ 529 \times 10^{-4}$
second angle	radian(rad)	$4.848\ 137 \times 10^{-6}$
ton (short, 2000 lbm)	kilogram (kg)	$9.071\ 847 \times 10^{2}$
watt-hour	joule (J)	$3.600\ 000^{*} \times 10^{3}$
yard	meter (m)	$9.144\ 000^{*} \times 10^{-1}$
yard^2	meter^2 (m^2)	$8.361\ 274 \times 10^{-1}$
yard^3	meter^3 (m^3)	$7.645\ 549 \times 10^{-1}$

*Exact

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